Arthropod cuticle

Research on arthropod cuticle as a multifunctional composite material and application of abstracted principles to architecture

Winter term 2013/14
Module 011600801
Module 011300605

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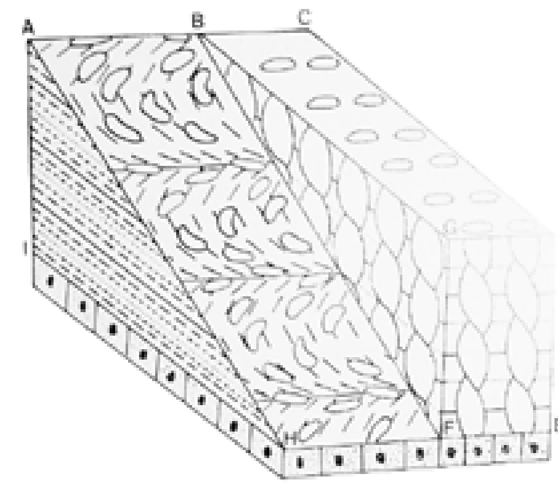
Introduction

Arthropod cuticle is a multilayered multifunctional composite material, which plays both roles of a shelter and a skin.

Our goal is to create responsive architectural skin with passive actuation.



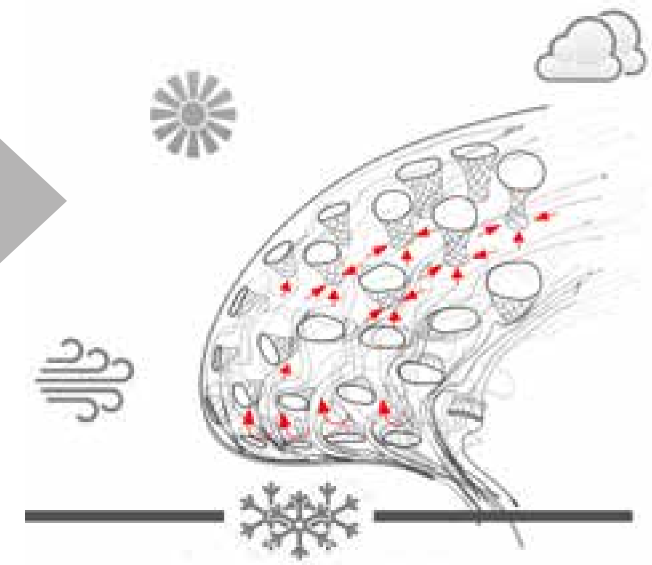


FIGURE 01: Scheme of porous cuticle (*Source: Biology of the Arthropod Cuticle*. A.C. Neville. Springer-Verlag. 1975)

FIGURE 02: Scheme of responsive architectural skin with openings

INTRODUCTION

Arthropod exoskeleton (cuticle) is a multilayered multifunctional composite material, which plays both roles of a supporting structure of the body and a skin. Exoskeletons fulfil a set of functional roles including protection, excretion, sensing, support, feeding, acting as a barrier against desiccation in terrestrial organisms, and in providing an attachment framework for musculature.
We have studied five main cuticle principles which were abstracted and can be applied to architecture to create multifunctional multilayered shell. These principles are:
1. Multifuntional Skin,
2. Multilayered Composite,
3. Anisotropic Material,
4. Porous Material,
5. Water sensible system.

Our goal is to create responsive architectural skin with passive actuation. The main abstracted principles, that found it's architectural application in models are:
1. Opening/closing of exterior stiff elements (based on biological role model of stiff elements- schlerites which are connected by flexible tissue).
2. Outer layer bares loads, inside layer is changeable, able to open and close pores (based on biological role model of multilayered multifunctional skin).
3. Shape of pores is changing (based on biological role model of reorganisation of chitin fibers in connection with shrinkage/expansion).
As a result we created a system of openings which are connected by fibers. The actuation of fibers causes a change of the openings' shape (they can close and open by compression or rotation). The actuation also has influence on global shape.

Chapter 02
Cuticle Composition

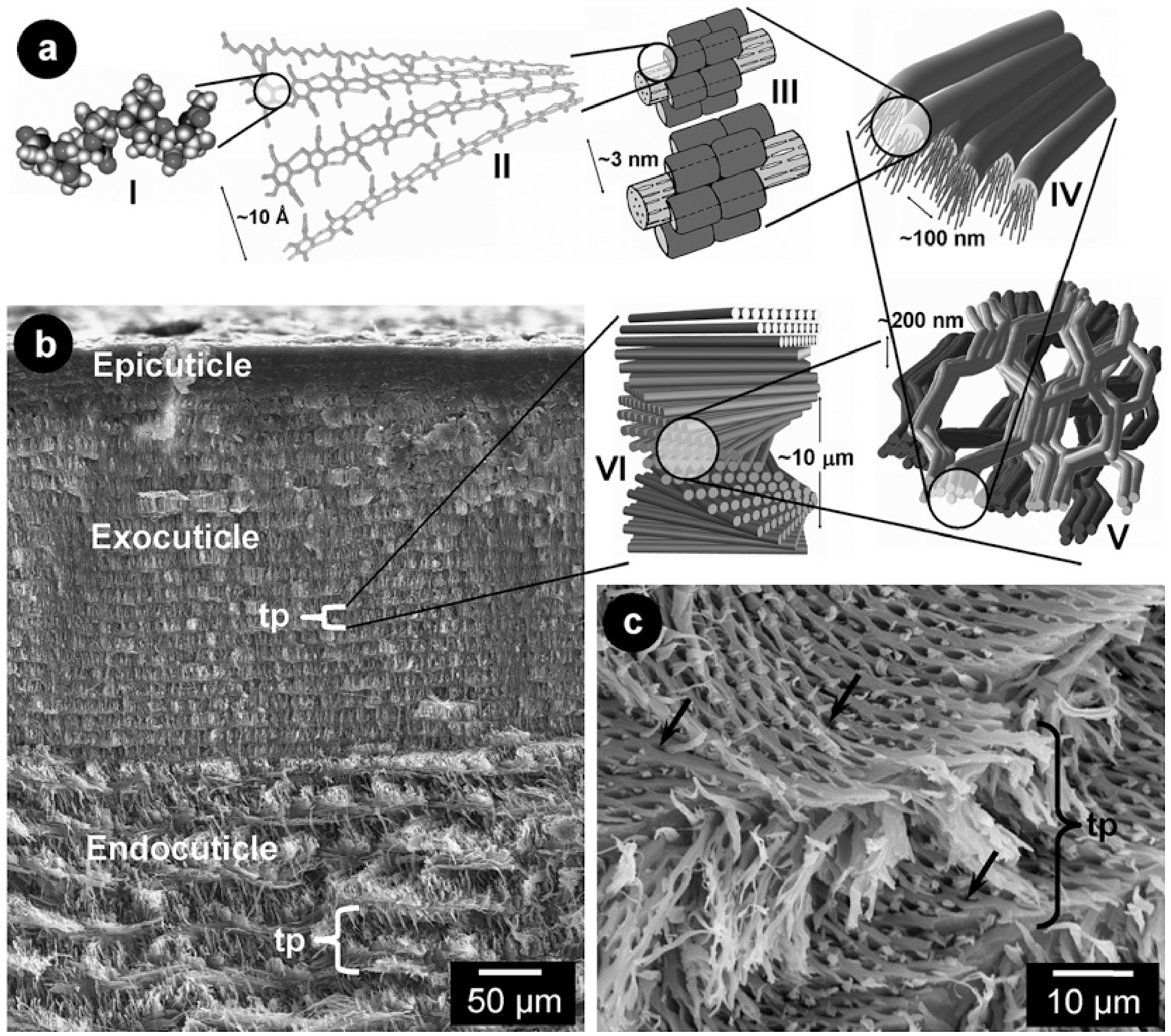


FIGURE 03: Microstructure of lobster cuticle. (a) Schematic representation of the different hierarchical levels in the microstructure of lobster cuticle starting with the N-acetyl-glucosamine molecules (I) forming anti-parallel a-chitin chains (II). Between 18 and 25 of these molecules wrapped with proteins form nanofibrils (III), which cluster to form chitin protein fibers (IV) that are arranged in horizontal planes in which the long axes of the fibers are all oriented in the same direction. The fibers are arranged around the cavities originating from the extremely well-developed pore canal system which gives the structure a honeycomb-like appearance (V). These chitin protein planes are stacked with the orientation of the fibers in superimposed layers rotating gradually around the normal axis of the cuticle, thus creating a typical twisted plywood structure (VI). (b) SEM micrograph showing a cross-section through the threelayered cuticle. The different stacking density of the twisted plywood layers (tp) in the exo- and endocuticle can be clearly seen. (c) SEM micrograph of obliquely fractured endocuticle displaying two superimposed twisted plywood layers (tp) and showing their typical honeycomb-like structure. The arrows indicate the pore canals. (*Source:The exoskeleton of the lobster Homarus americanus as an example of a smart anisotropic biological material.* P. Romano, H. Fabritius, D. Raabe)

Cuticle Composition

Components of Cuticle

CHITIN + MATRIX of PROTEIN
WATER
POLYPHENOLS
LIPIDS
MINERALS

nanofibrils → **microfibres** + **matrix**

chitin molecules wraped by proteins → aggregation of nanofibrils

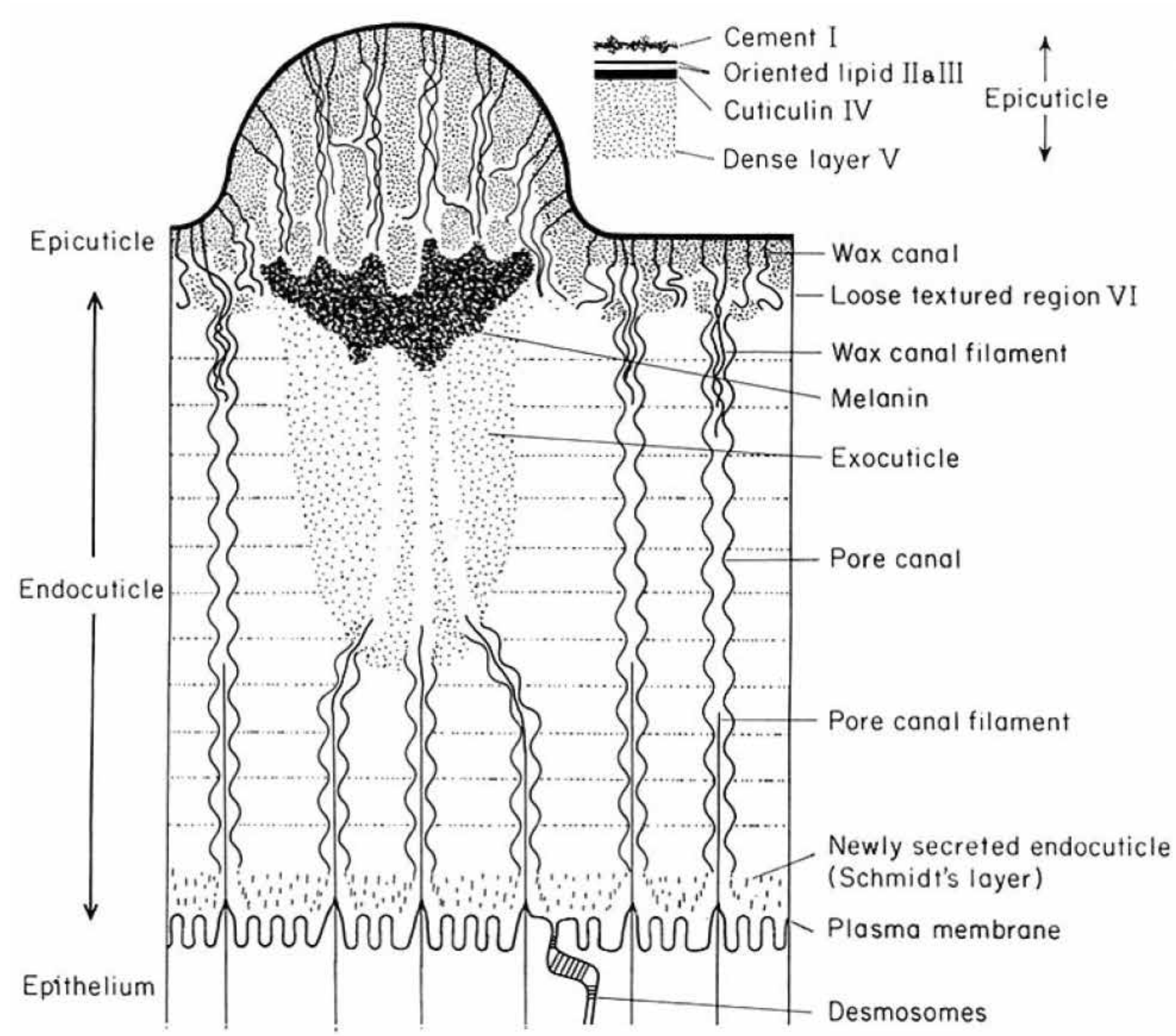


FIGURE 04: Diagram of the structure of the abdominal cuticle in Galleria Larvae. (Source: *Pore Canals and Related Structures*. M. Locke)

The cuticle is a hierarchically structural fibre-based composite material based on chitin (H. Fabritius and Raabe, 2011).

Chitin is a polysaccharide molecule, caracterized by its solubility, elasticity and resistance to crack expansion.

We can talk about 6 hyerarchical levels at the structure of cuticle (fig.03. a):

1.In arthropod cuticle the acetyl glucosamine monomer represents the lowest level of structural hierarchy.

2. Crysralline chitin is the second.

3. At the third level 3 polymrphic forms have been found that differ in the arrengement of the molecular chains: α-chitin; β-chitin; γ-chitin.
In arthropod cuticle the α-chitin predominates.

4. 18 to 25 chitin molecules wrapped by proteins form nanofibrils with diameters between 2 and 5nm and lengthsof about 300 nm.

5. The chitin wrapped: nanofibrils aggregate to form 50250 nm thick chitin-protein fibers.

6. Chitin-protein fibers are organized in parallel forming planar arrays. These fibrous sheets form stacks in which the long axis of the fibers gradually rotate around the normal axis of the cuticle from one sheet to the next, creating a twisted plywood (helycoidal arrengement) or show a preferred direction (unidirectional arrengement).

Chapter 03
Types of Cuticle

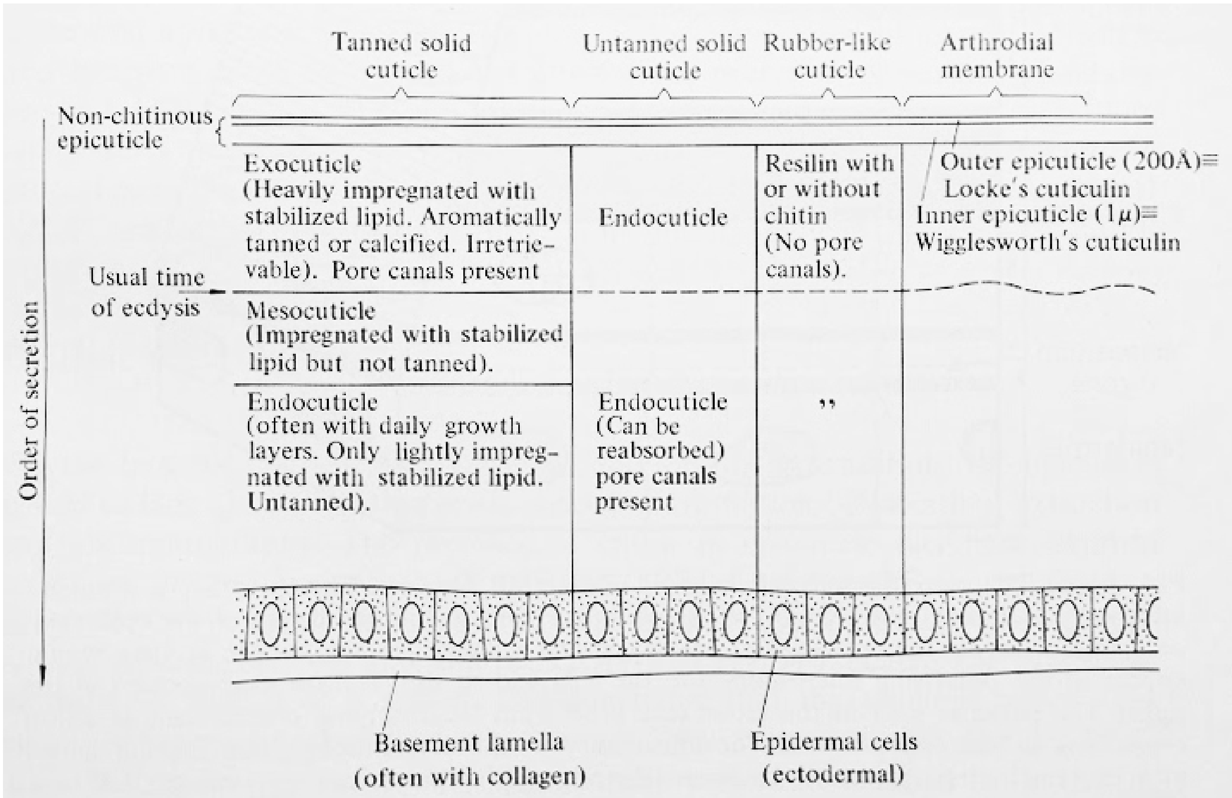


FIGURE 05: Basic plan of arthropod cuticle (*Source: Biology of the Arthropod Cuticle*. A.C. Neville. Springer-Verlag. 1975)

Layers in cuticle

The exoeskeleton of insects is divided in two parts: Epicuticle and Procuticle

1. Epicuticle
It is a non-chitinous region containing different quinones and tanning agents, lipids and proteins. It conforms a barrier against dehydration and swelling.

It is composed by four different layers:

1.1. Cement Layer: The most outer layer of the exoeskeleton. Probably consisting of proteins and polyphenols. It is not existing in all the insects (bees are for instance lacking this layer).

1.2. Wax layer: It is thought to be secreted via canals from the epidermis just prior to ecdysis. This layer is very important for the control of permeability of the cuticle, helping to avoid the loss of water.

1.3. Outer epicuticle: It is important in surface pattern determination.Into it insert muscle attachment fibers.

1.4. Inner epicuticle: Isotropic. Contains a high iron concentration.

2. Procuticle
It is composed by chitin fibers embedded in a matrix of proteins.

Divided in two different layers:

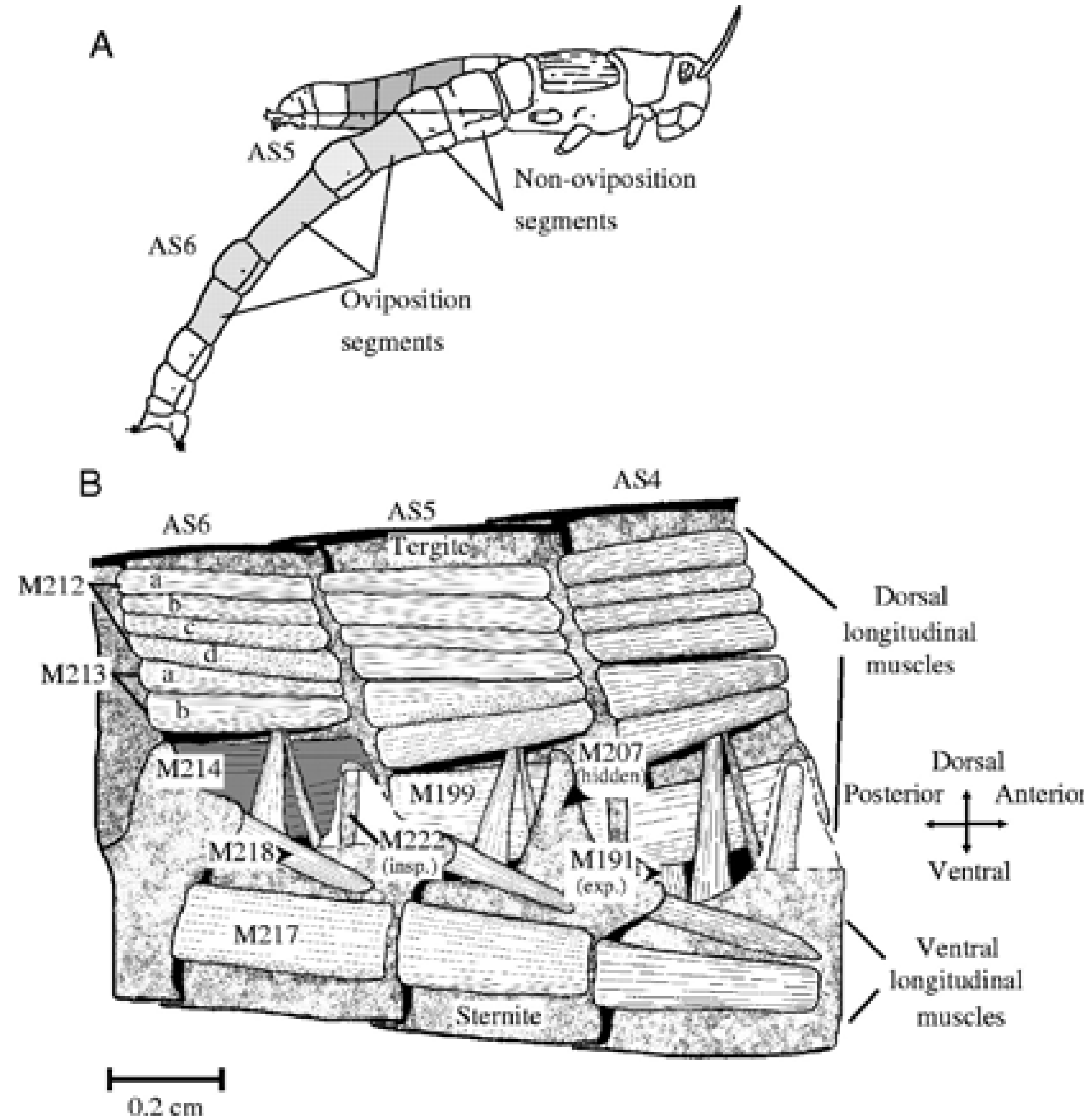


FIGURE 06: Sketch of an ovipositing locust. (Source: J Exp Biol. October 2001. vol. 204 no. 20 3531-3545 (Adapted from Rose et al., 2000)

2.1. Exocuticle: It is highly sclerotized. Usually denser than the endocuticle and stiffer.

2.2. Endocuticle: It is less sclerotizes and less stiffer. Often is thicker than the exocuticle.

Types of Cuticle

1. Solid cuticle: Stiffer
We can find this type of cuticle at the sclerites.

It usually contains 15-30% dry weight fraction of chitin and around 12% water.

The hardness is due to impregnation and tanning and not to chitin. The hardest cuticles have a relatively higher proportion of exocuticle.

2. Arthrodial membrane cuticle: Soft and Flexible.
It is the kind of cuticle we can find between the sclerites, permitting its movements.
It contains equal fraction of chitin and protein and 40 - 75% water.

3. Rubber-like cuticle: Extensive and reversible elasticity.
This type of cuticle forms the ligaments in the wing base of insects.
Containing a true elastomer protein: Resilin, highly hydrated. If it is stretched 97% of the applied energy can be recovered on release, so that just 3% of energy has been lost as heat.
Its function is to assist muscles by storing and releasing elastic energy.

Chapter 04
Studied Cuticle Principles

1. Multifuntional Skin

2. Multilayered Composite

3. Anisotropic Material

4. Porous Material

5. Water sensible system

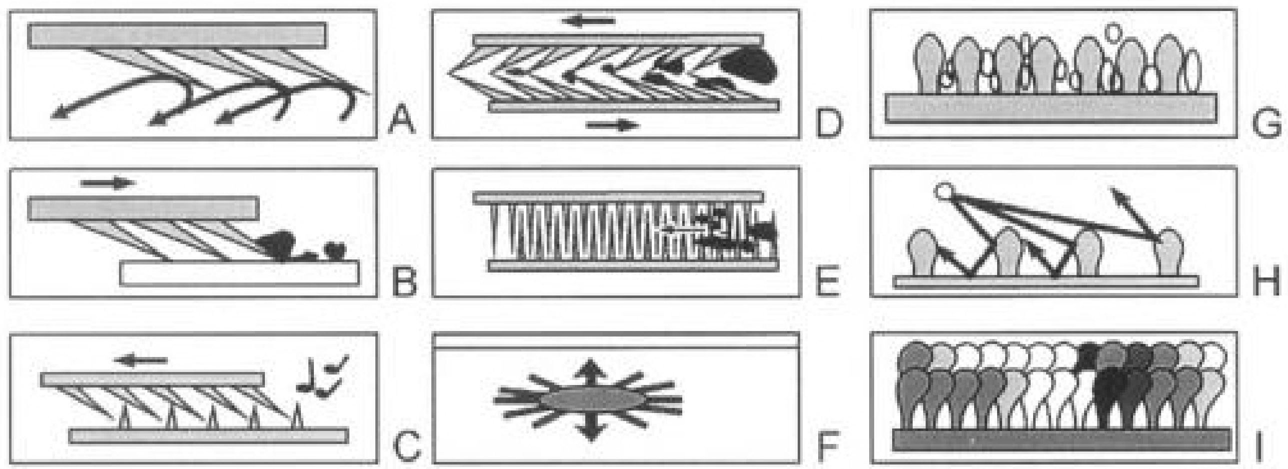


Figure 07: Diagram of functions of cuticular microstructures. A. As aerodynamically active surfaces. B. Grooming. C. Sound generation. D. Food grinding. E. Filtration devices. F. As hydrodynamically active surfaces. G. Oxigen retention. H. Thermoregultion. I. Body coloration pattern. (Source: *Attachement Devices of Insect Cuticle.* Stanislav Gorb. Kluwer Academic Publishers. 2001)

1. MULTIFUNTIONAL SKIN

The exoeskeleton of insects, the cuticle, is a multifunctional skin able to perform an amazing range of different functions:

- Structure
- Locomotion
- Defense
- Humidity and temperature modulation
- Sensorial perception of the environment
- Self-reparing system
- Transport of epidermal secretions
- Metamorphosis by moulting

Apart of this general missions, each species has developped special cuticular microstructures which are able to carry out many more specific tasks:

- Aerodinamically active surfaces
- Grooming
- Sound generation
- Food grinding
- Filtration devices
- Hydrodinamically active surfaces
- Oxygen retention
- Thermoregulation
- Body coloration pattern

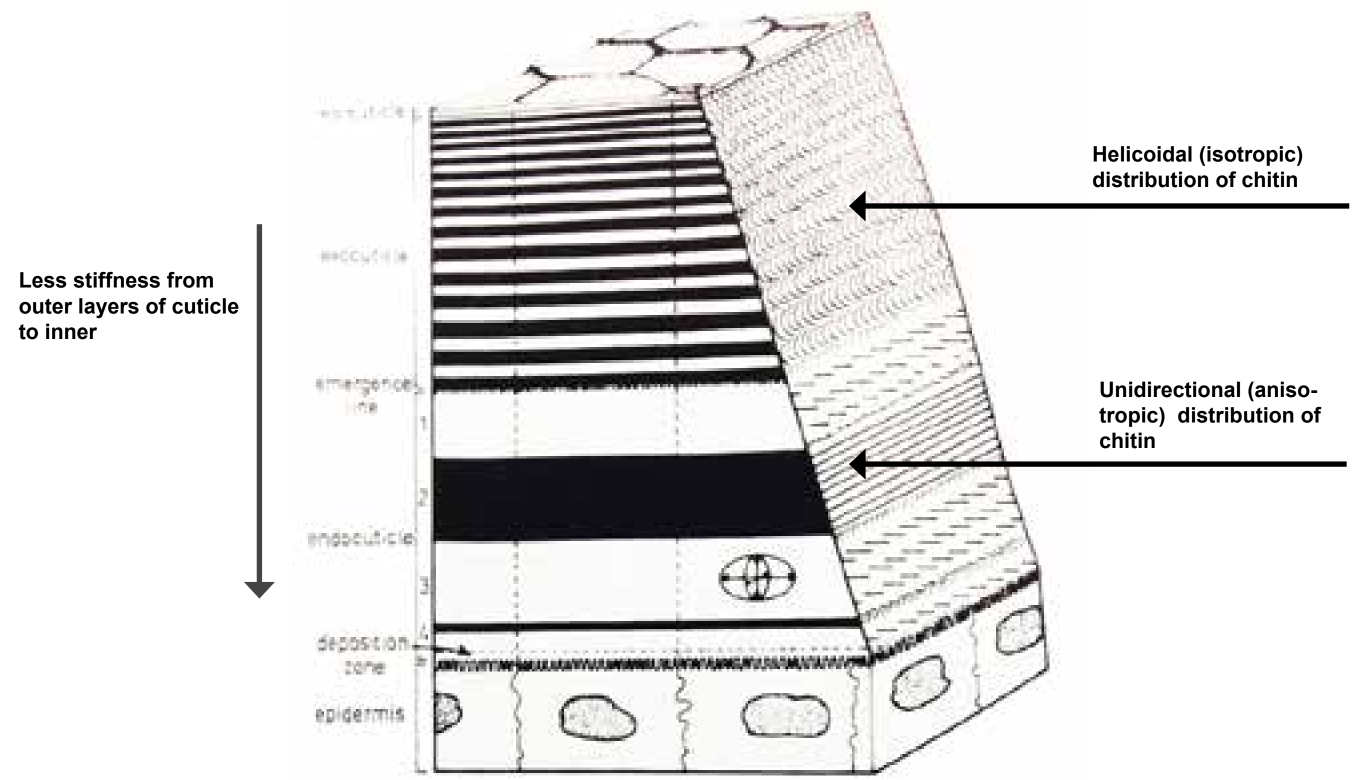


FIGURE 08: Diagram of insect cuticle based upon adult Tenebrio.
(Source: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975.)

2.MULTILAYERED COMPOSITE

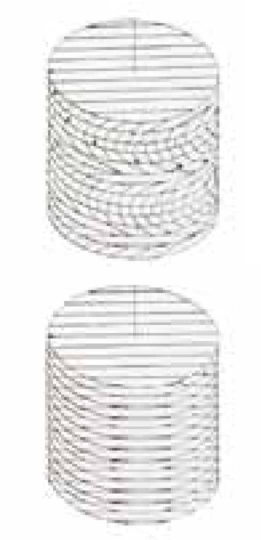
Two-system model of cuticle architecture

Two systems are layers in which the chitin micrifibrils are helicoidally arranged in a protein matrix, and layers in which microfibrils are all unidirectionally oriented to form a preferred layer.

This information was in fact first deducted from the orientations of pore canals in these layers.

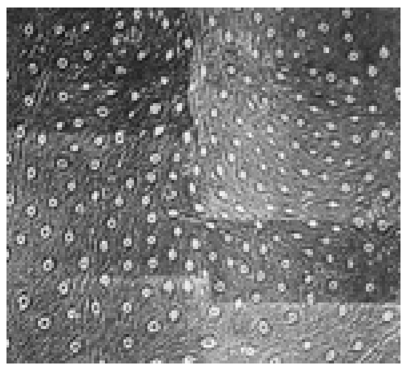
Most exocuticles are helicoidal (lamellate) through their thickness. It is in endocuticles that interesting sequences and relative proportions of helicoidal and unidirectional layers are found. When both orientations are present, one or the other may predominate.

Fibres orientation



Helicoidal (isotropic) distribution of chitin → regular position

Unidirectional (anisotropic) distribution of chitin → preffered direction



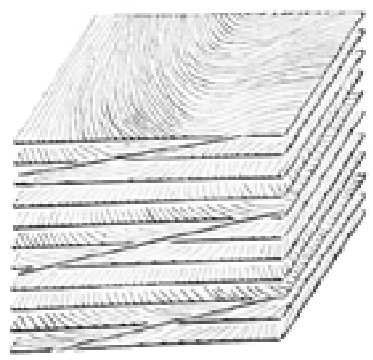


FIGURE 09: Pattern of one layer. (Source: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975.)

FIGURE 10: Multiple layers in helicoidal position. (Source: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975.)

3.ANISOTROPIC MATERIAL

Unidirectional (anisotropic) and helicoidal (isotropic) distribution of chitin is noticed in layers of cuticle.Helicoidal is a regular position, unidirectional distribution creates preffered direction of cuticular fibers.

Reorganisation of chitin

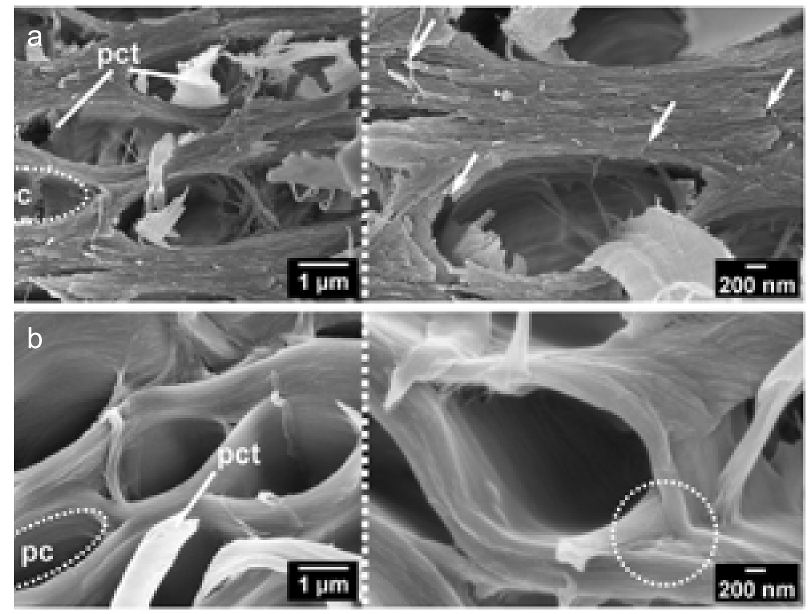
Fraenkel and Rudall (1947) recorded changes in the X-ray diffraction pattern during the formation of the puparium of Sarcophaga. The disposition of chitin fibres changed from regular (helicoidal) to the planes parralel to the surface.

Reorientation is indipendent of both hardening and darkening. Secondary reorientation of chitin also does not involve muscular contraction.

Examples of reorganisation of chitin:

- during contraction of the last larval cuticle to form the puparium in Diptera.
- in locust exocuticle during expansion following acdysis.
- along the vein axes in butterfly wing during expansion following acdysis.
- plasticizing and expanding of Rhodnius abdomen.

Internal pressure is required for reorganisation of chitin.



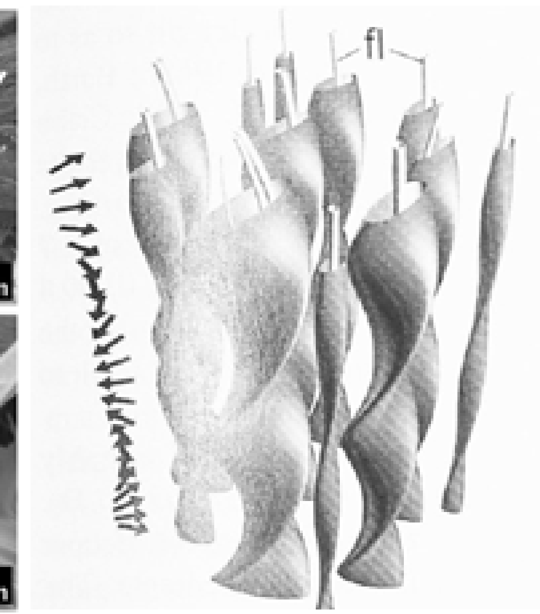


FIGURE 11: Microstructure of lobster endocuticle fractured parallel to the surface. The SEM micrographs are overviews (left) and detail images (right) of
untreated and chemically treated material. (a) Untreated cuticle, overview showing thick walls around the pore canals (pc) and residues of the tubes (pct)
therein. The detail image shows the discontinuous, blocky fiber structure with numerous broken fiber ends (arrows). (b) Decalcified cuticle (EDTA,
0.15 M), overview with pore canals (pc) and pore canal tubes (pct). The high-resolution image shows the smoothness of the thin-walled structure and the
way how separate fiber bundles contact each other to form the corners of the pore canals (encircled area). (Source: *The exoskeleton of the lobster Homarus americanus as an example of a smart anisotropic biological material. P. Romano, H. Fabritius, D. Raabe)*

FIGURE 12: Vertical filaments in ribbon like pore canals. (Source: *Attachement Devices of Insect Cuticle.* Stanislav Gorb. Kluwer Academic Publishers. 2001)

4. POROUS MATERIAL

The arthropod cuticle is a extremely well developed pore system which noumerous canals penetrate it perpendicular to de cuticle outer surface.

The apical face of the epithelial cells is extended as numerous narrow cytoplasmatic filaments in the pore canals running across the procuticle and the epicuticle.

The pore canal filament may be the mechanism by which the cells keep a hole in the newly secreted cuticle until the hardening is complete, by inhibitinf fiber formation. It may act also as anchor to stick the epithelium to the endocuticle.

We can the talk about diffrent functions:

- Transport of substances: wax, tanning agents, adhesive secretions...

- Contribution to lightness

- Contribution to flexibility

- Reduction of brittle fracture

- Pore Canal Filaments:
  May act against delamination
  May help to the creation of pore canals

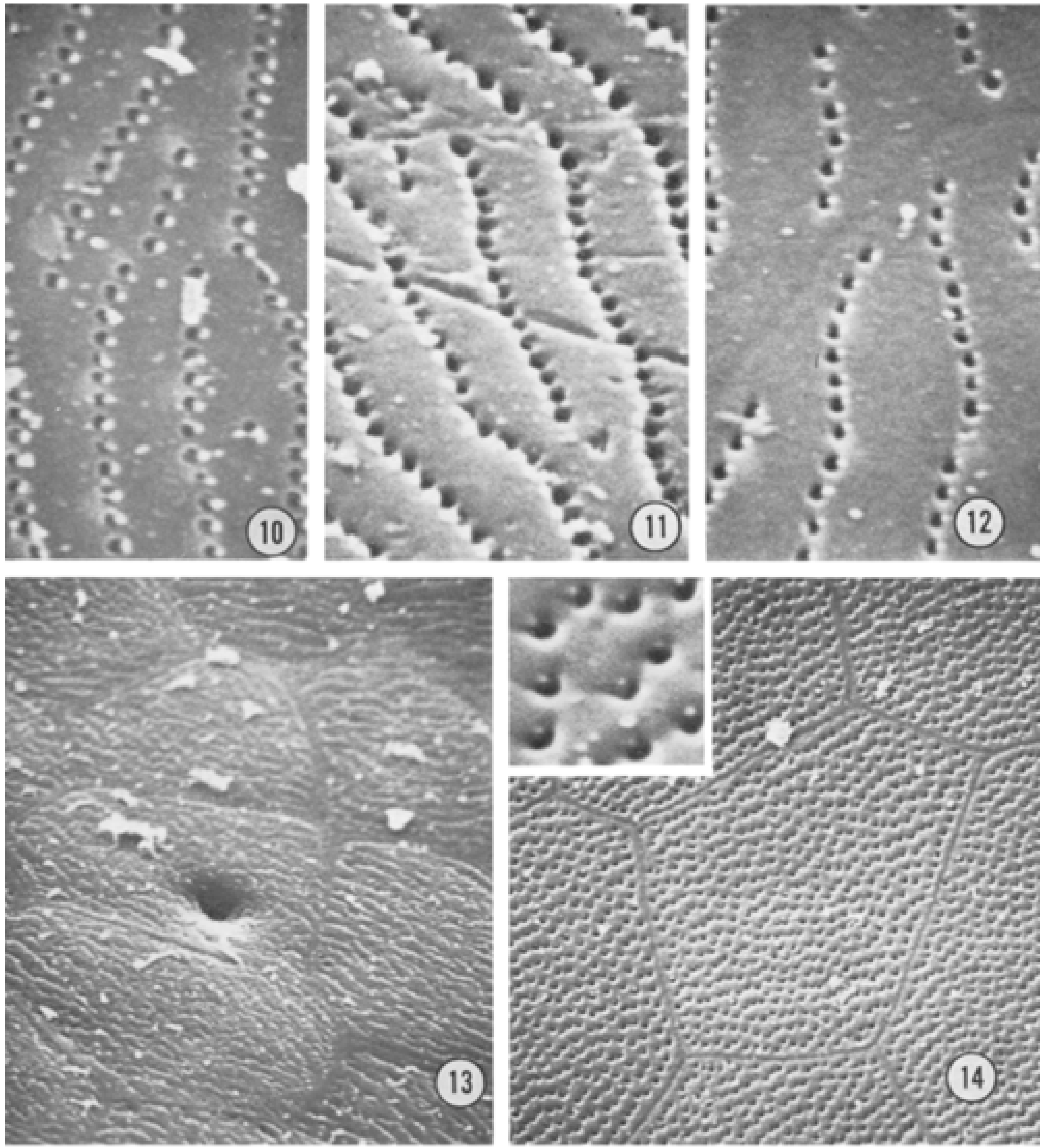
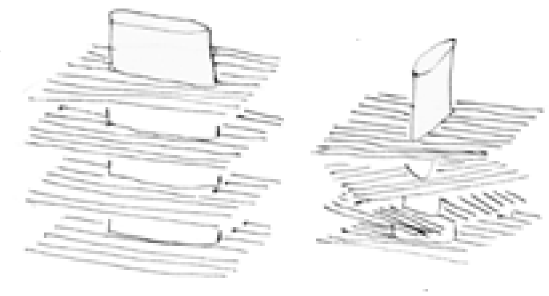


FIGURE 13: Disposition of pores is based on disposition of epidermal cells. (Source: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975.)

The disposition of chitin fibres can change.

Pore canals shape is formed by the position of chitin layers.

Reorganisation of chitin fibers influences the shape of pores.



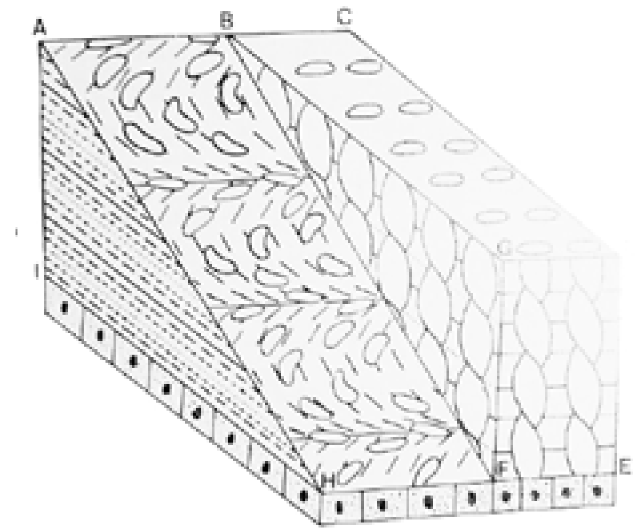


FIGURE 14: Pore canal model.
(Source: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975.)

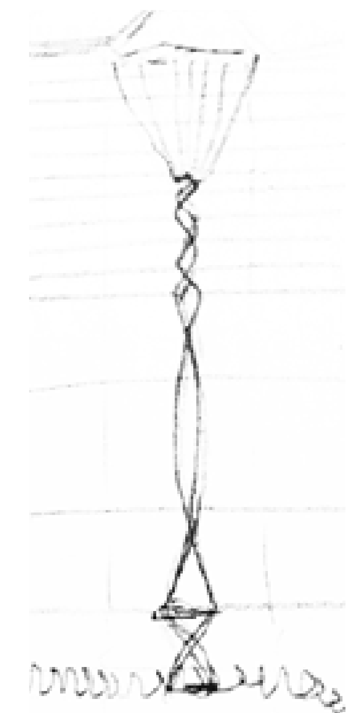


FIGURE 15: Difference in pitch in pore canal depends on disposition of chitin fibers.

Influence of reorganisation of chitin on pore canals shape.

In crustaceans shape of pores is round or elliptical. In insects pores are ribbon-shaped.
Pore canals shape is formed by the position of chitin layers. Twist is a product product of the microfibrils orientation in rotated layers creating helicoidal lamellae.

Speaking about elliptical and ribbon-shaped pores, it was established by light microscopy that pore canals rotate when traversing helicoidal (lamellate) layers and run an untwisted course through unidirectional layers. The pore canal rotations are all in phase with each other and twist with the same sence. In Limulus Polyphemus exocuticle it was seen that the rotating pore canals remained in the register with lamellae even though lamellae periodicity varied considerably, both in the natural state and in swelling and shrinking experiments.

Depending on the thickness of helicoidal lamella, the pitch of the twist is higher or shorter.

Neville (1967) has shown that reorientation of chitin in locust can be monitored by distortion in pore canals, thus reorganisation of chitin fibers influences the shape of pores.

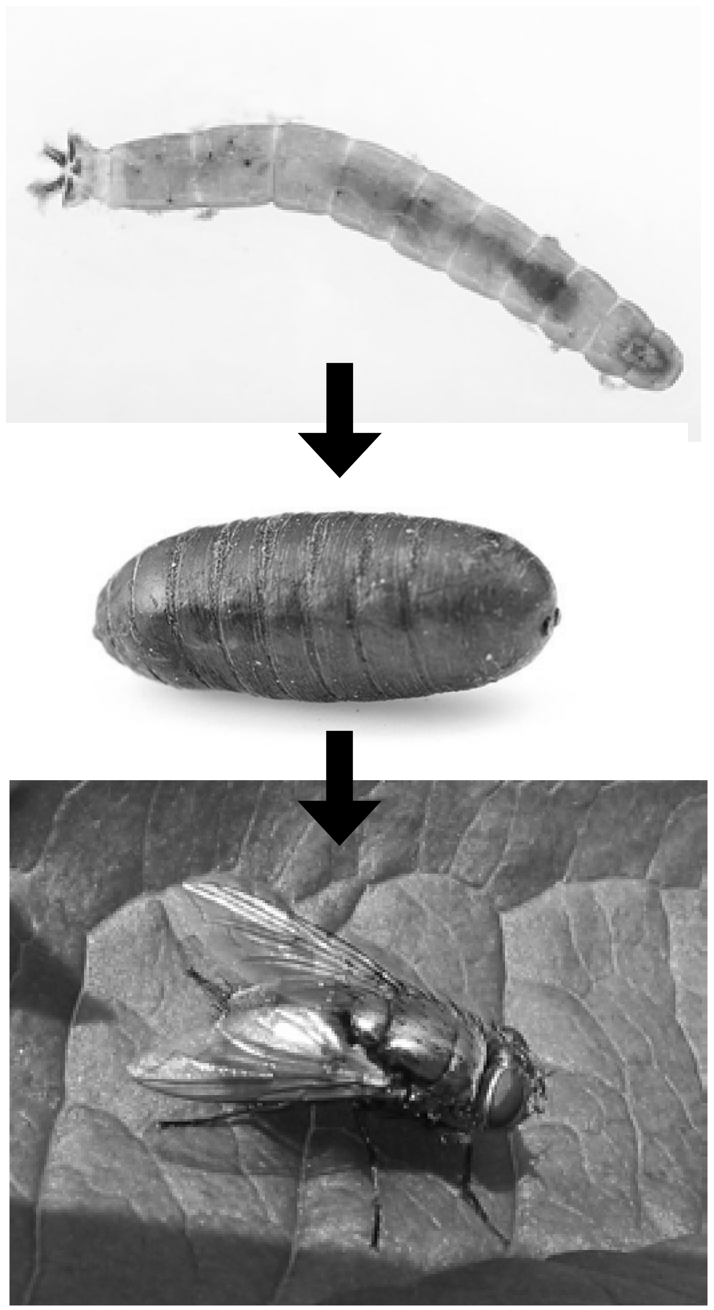


FIGURE 16: Example of shrinkage and reorganisation:
contraction of the last larval cuticle to form the puparium in Diptera

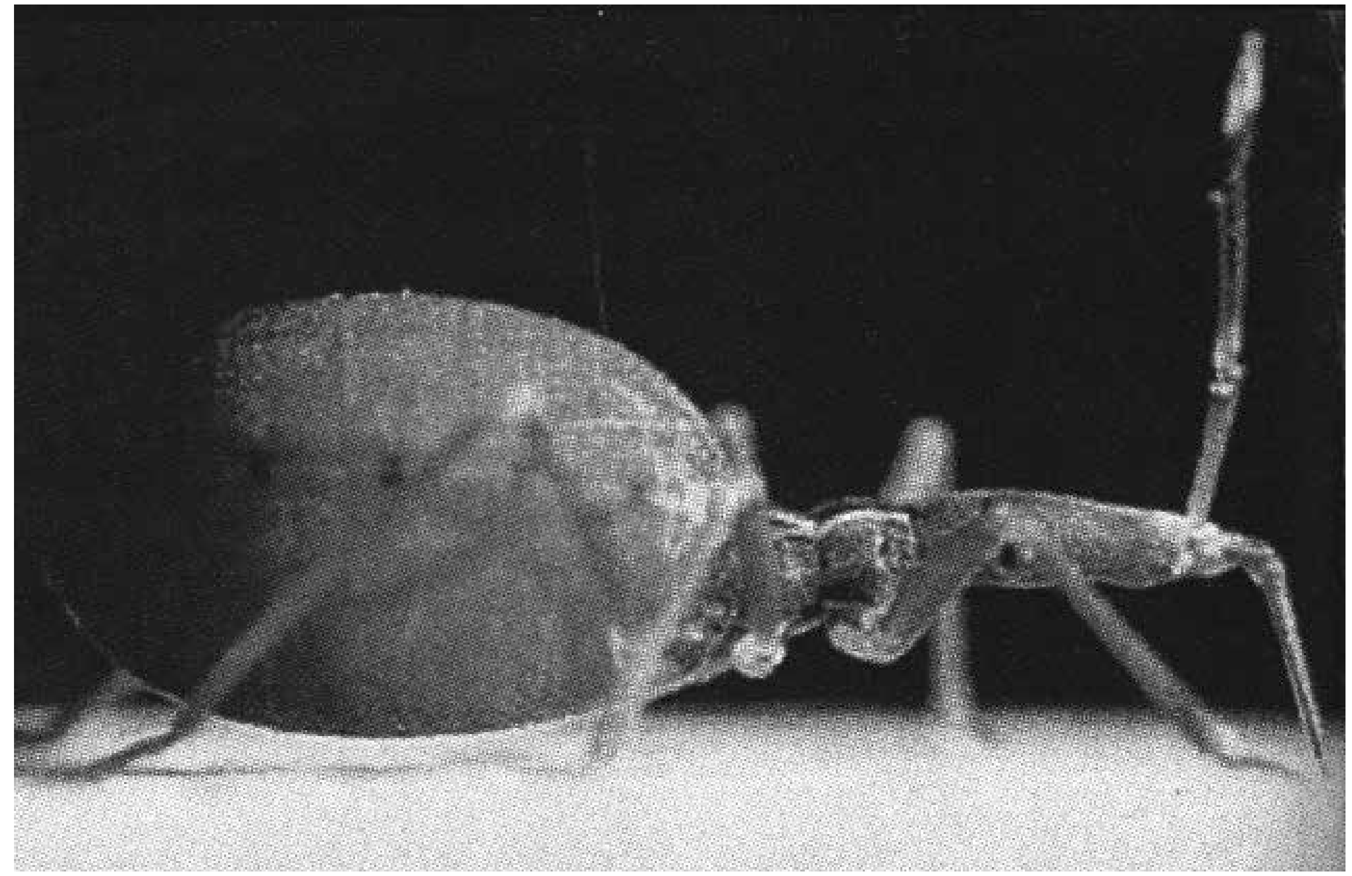


FIGURE 17: Abdominal cuticle of Rhodnius. Photo Larry Simpson.

Stiffness of cuticle depends on hydration degree

water content increase of 26 to 31% → reduction in stiffness from 250 MPa to10MPa → increase in extensibility from 10% to 100%

Endocuticle shrinkage following loss of water:

- Results in closer packing of lipid molecules at the outer surface
- Shrinkage of cuticula causes pore closing so the moisture can be saved

5. WATER SENSIBLE SYSTEM

“The hardness of a tissue, such as the cuticle, will be dependent upon the degree of hydration of its structure”. (Fraenkel and Rudall).

Cuticle can be mechanically extremely sensitive to water content. The secondary reactions made possible by the removal of water from the protein are much more important than the phenols in stiffening the cuticle, and that the control of stiffness is in general a matter of manipulating the water content. J.F.V. Vincent and U. G. K. Wegst, 2004).

Chapter 05
Abstraction of the
Role Model

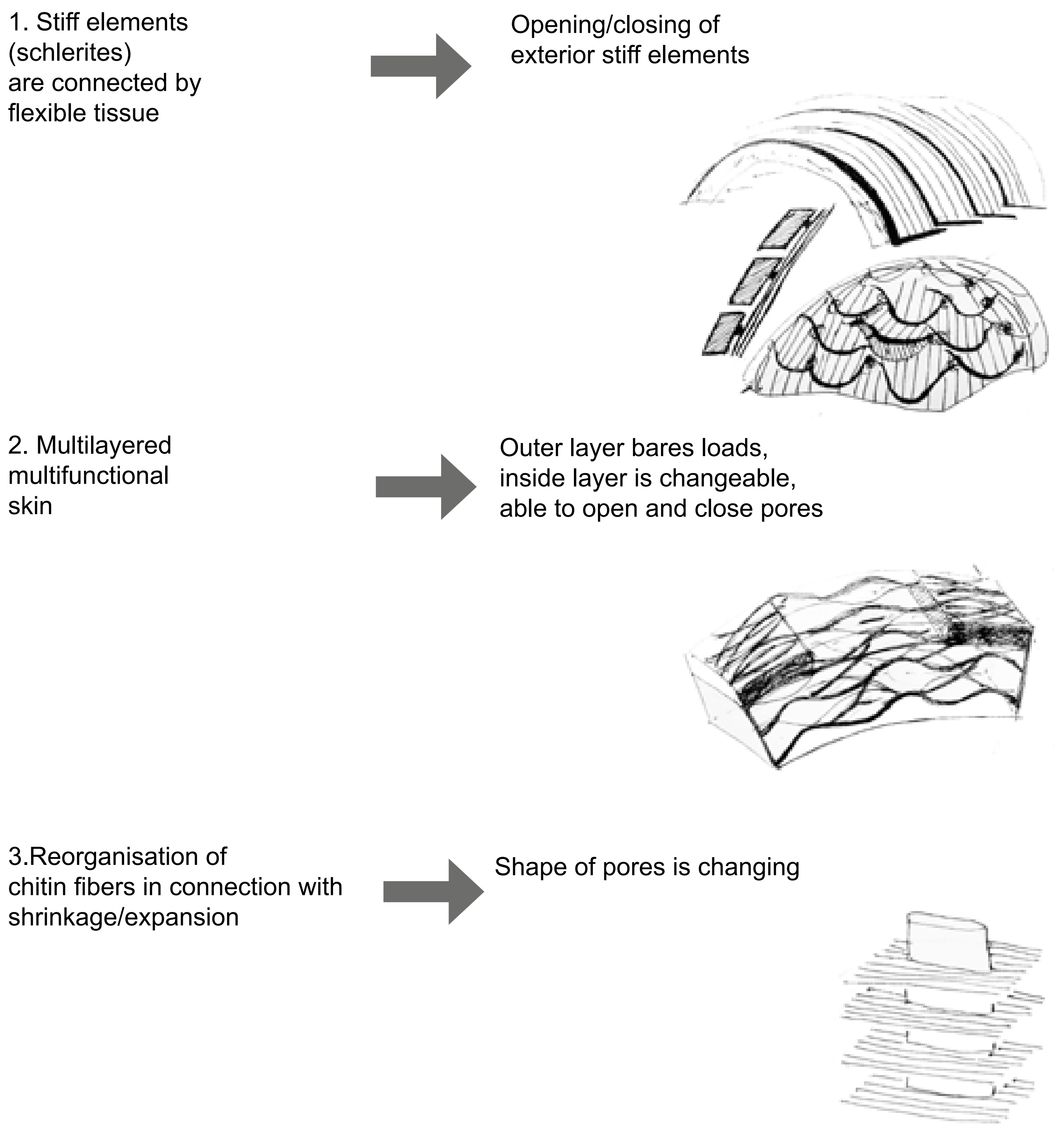


FIGURE 18: Abstraction of the role model.

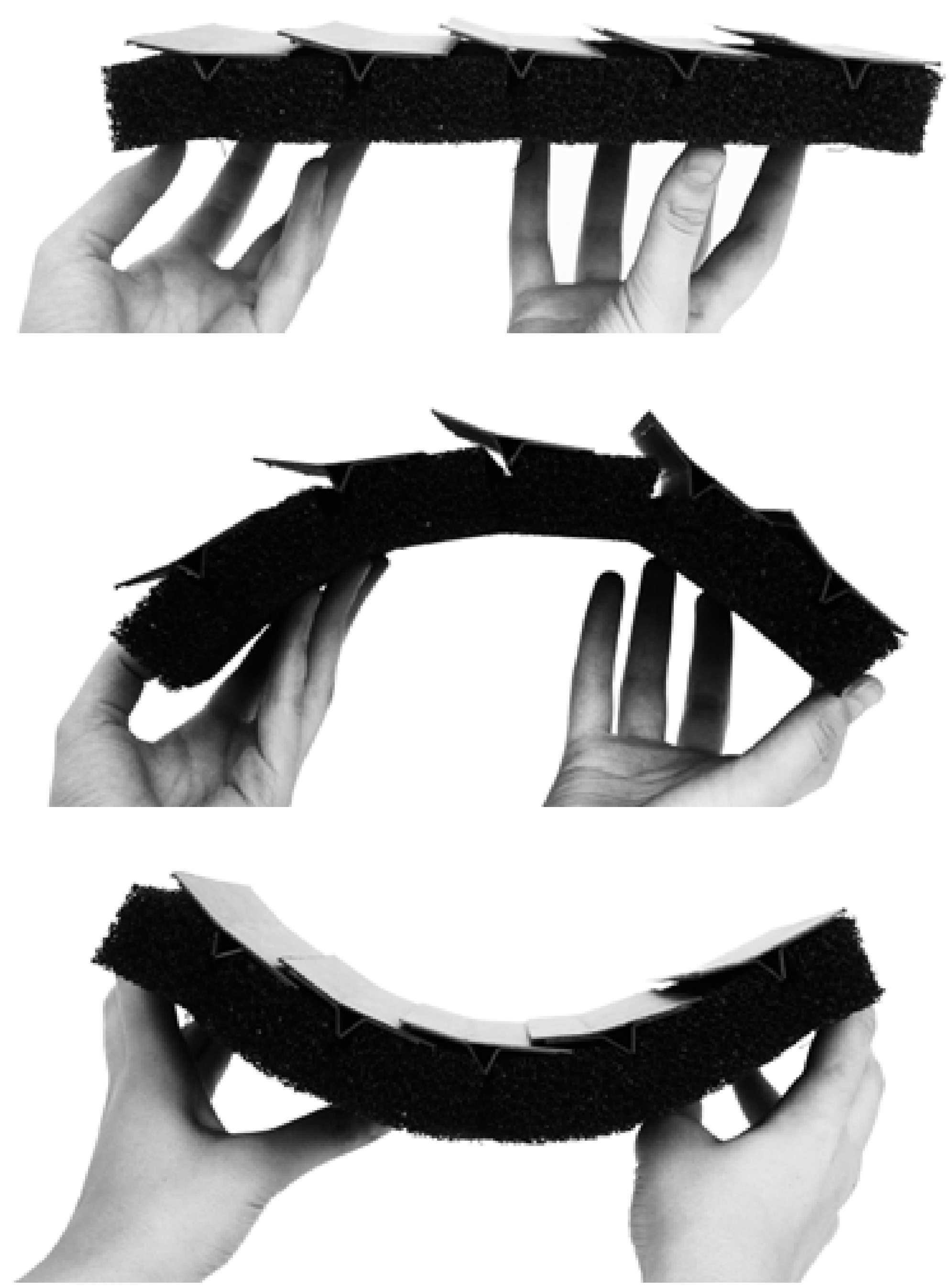


FIGURE 19: Model based on: anisotropical stiffness from inner to outer layers of cuticle.

ABSTRACTION OF THE ROLE MODEL

Models working due to principles found in arthropod cuticle were created in process of concepts abstraction. Models represent the principles of: solid stiffer cuticle on the outer layer with the possibility to open/close, being connected by flexible arthrodial membrane; reorganisation of fibers which may close pores by comressing or twisting them; vertical filaments in pore canals against delamination and for elastic energy storage; multilayered system with pore canals and rotation of system under vertical pressure; shrinkage/expansion of cuticle following reorganisation of fibres.

Solid stiffer cuticle on the outer layer as in the sclerites, being connected by flexible arthrodial membrane.
Opening/closing of sclerites follows movement of insect.

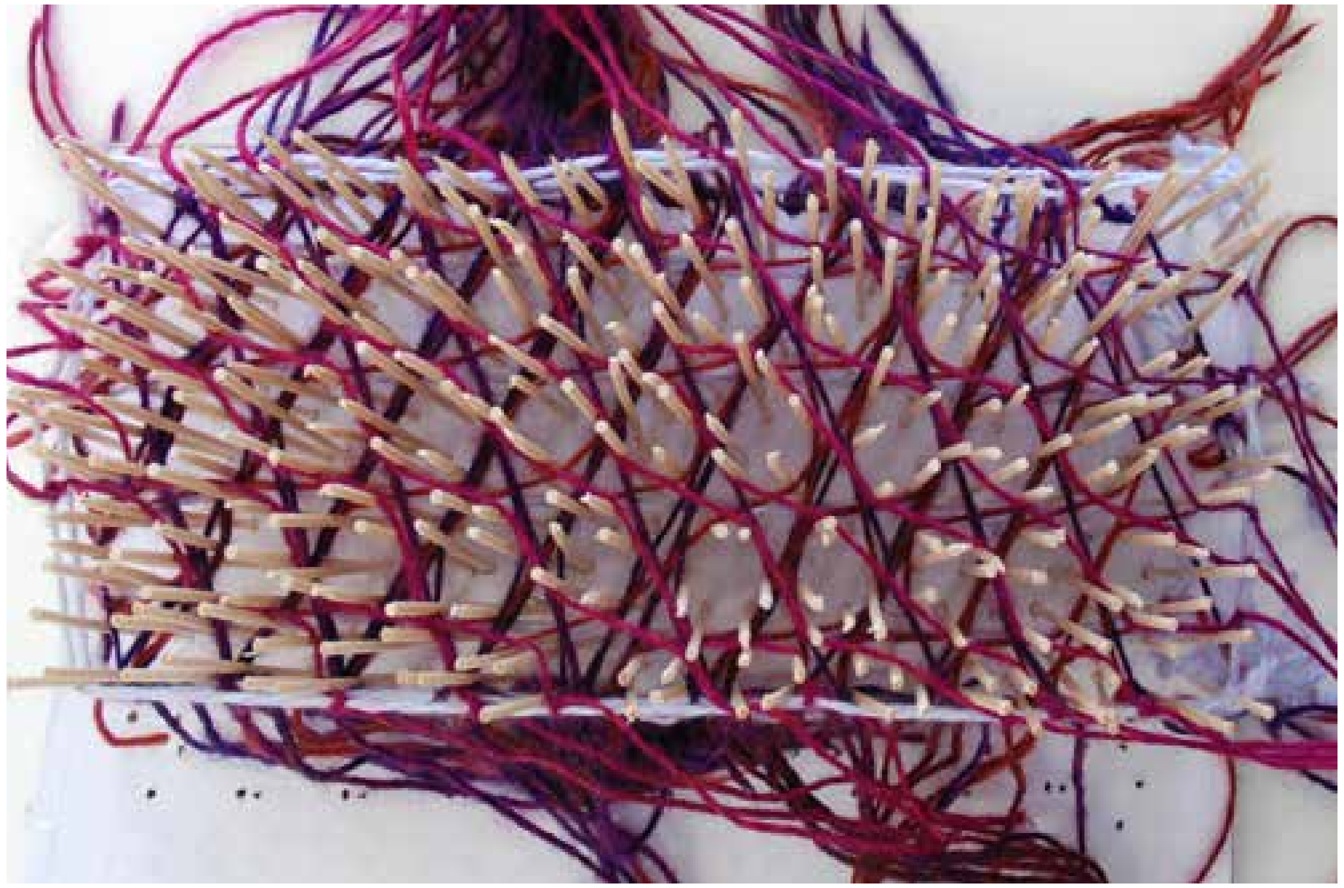


FIGURE 20: Model based on: helicoidal arrangement of fibers shaping pore canals.

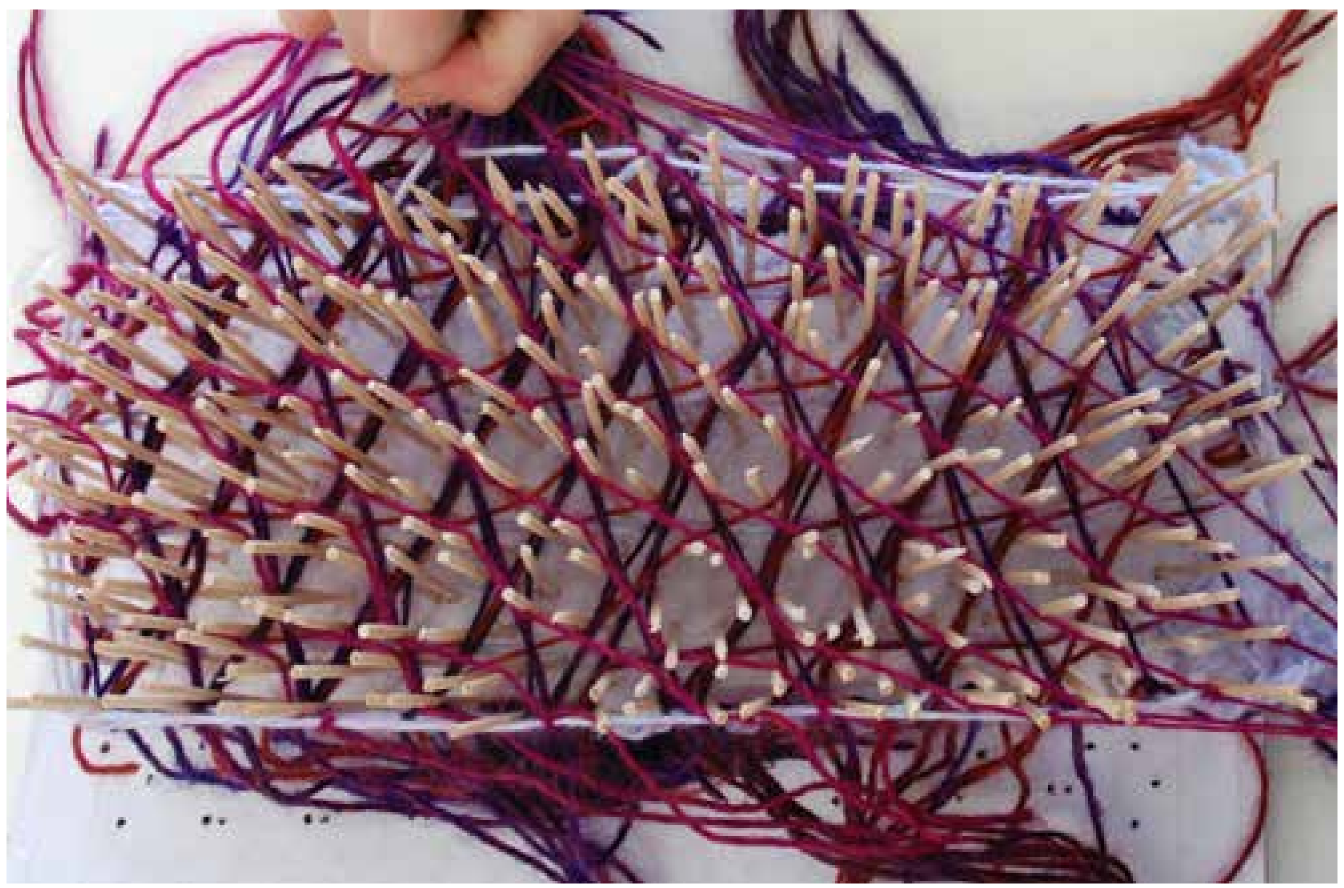


FIGURE 21: Model based on: reorganisation of fibers which may close pores.

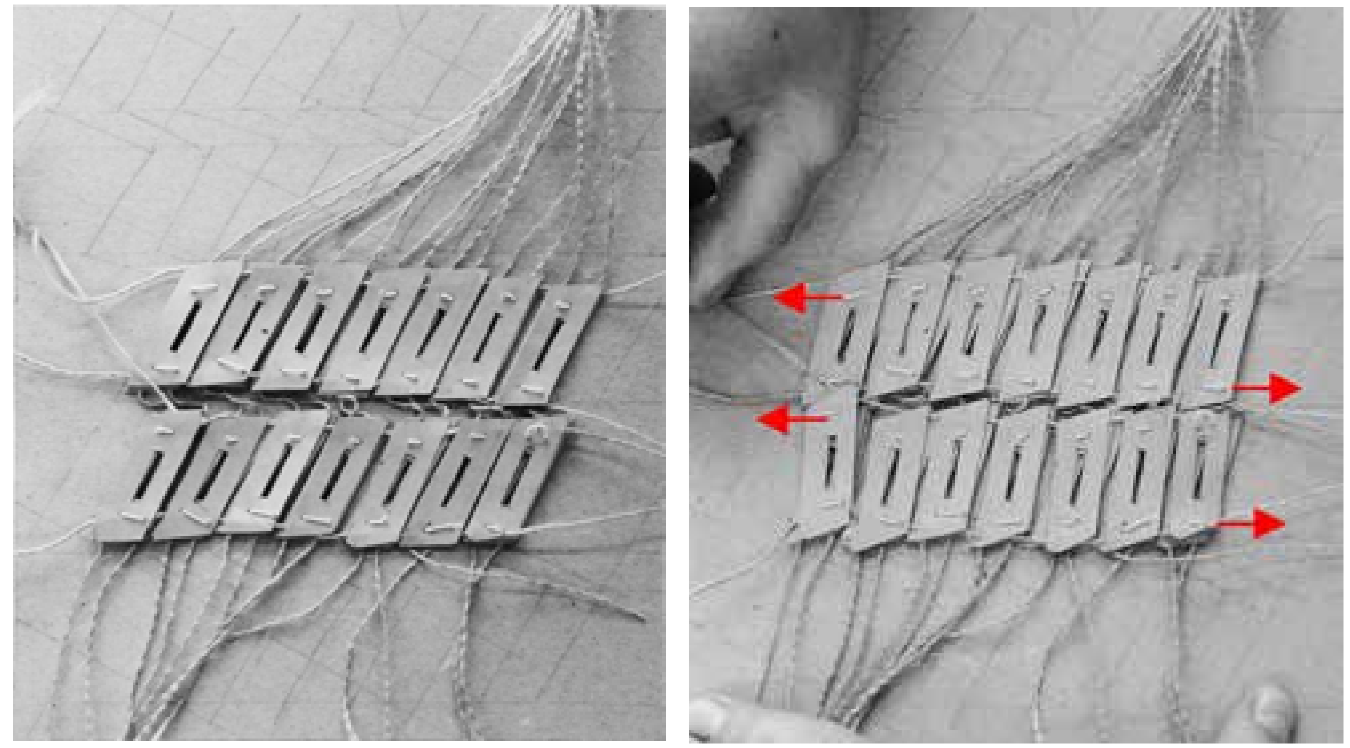


FIGURE 22: Model based on reorganisation of fibers. Transformation of fibers causes transformation of pore shape.

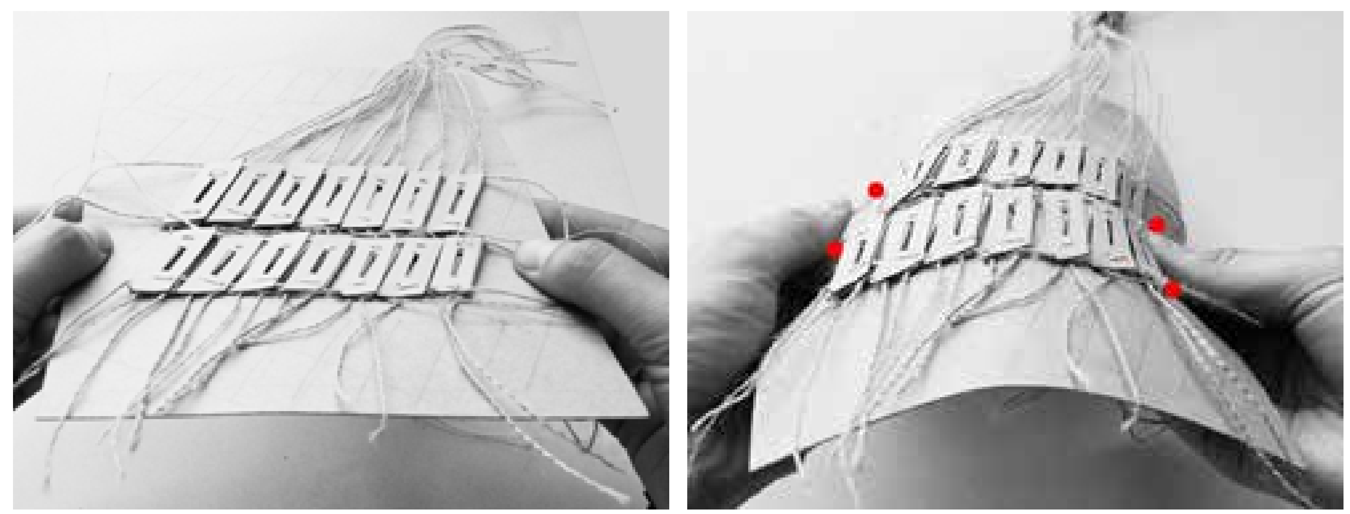


FIGURE 23: Model based on reorganisation of fibers. Transformation of general shape causes transformation of pore shape.

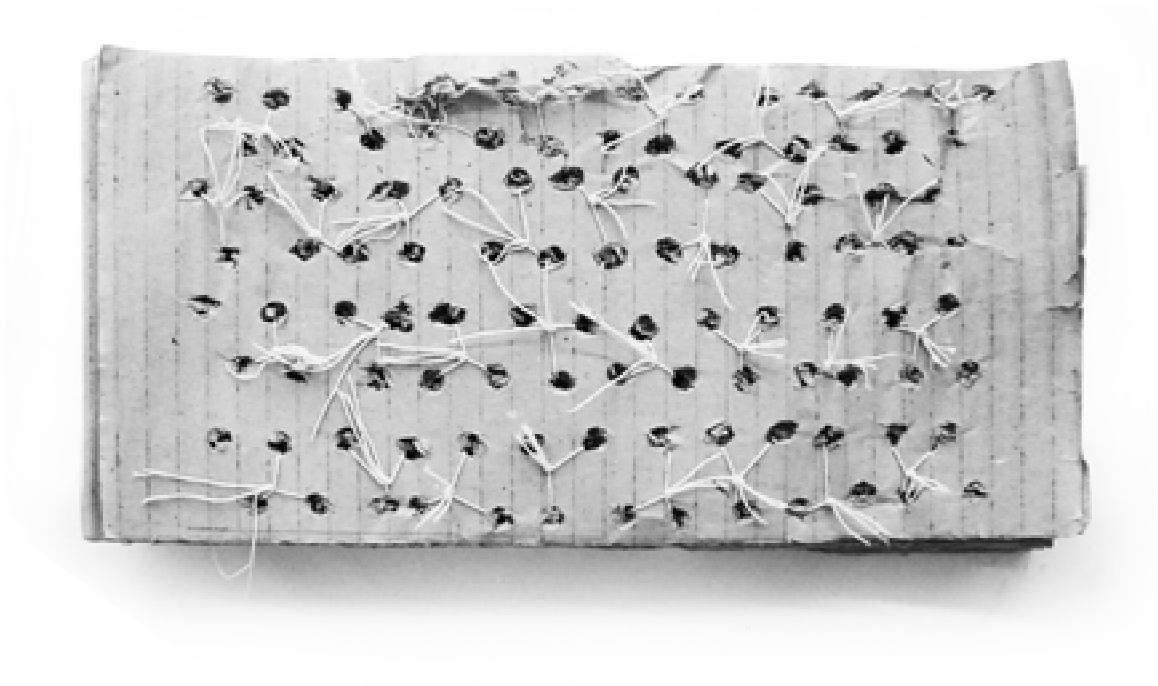


FIGURE 24: Vertical filaments against delamination.

FIGURE 25: Layers forced to change position : storing of elastic energy in vertical filaments.

FIGURE 26: Multilayered system with pore canals. Rotation of system under vertical pressure.

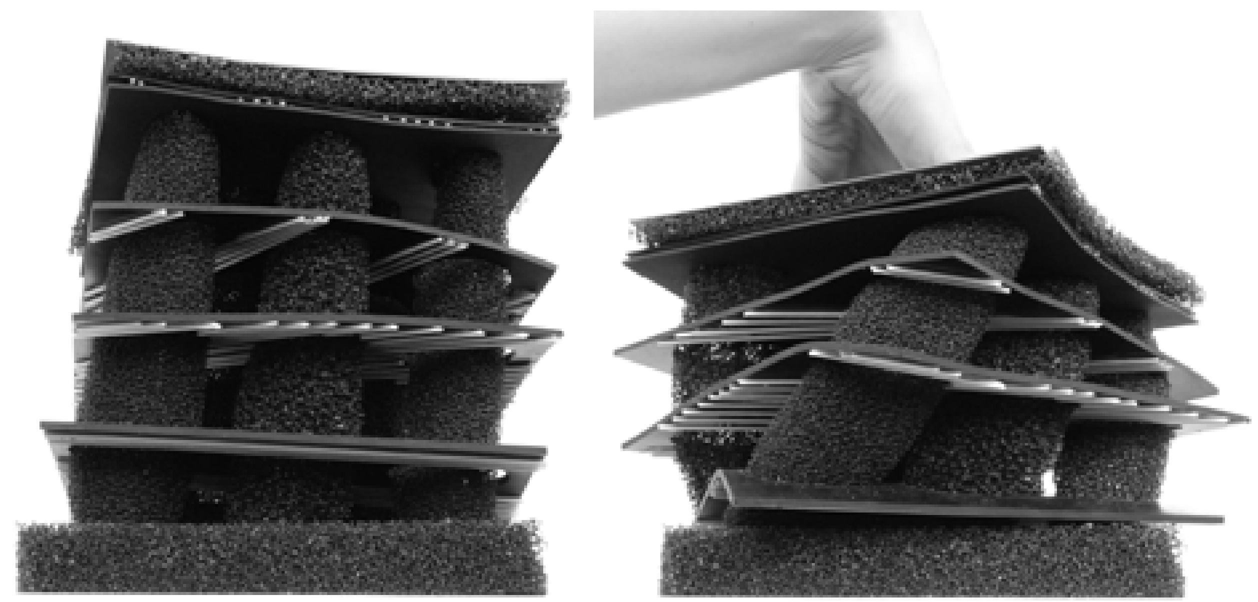


FIGURE 27: Models based on the reorganisation of chitin in cuticle. Layers forced to change position : storing of elastic energy in vertical filaments.

FIGURE 28: Model based on: shrinkage/expansion of cuticle following reorganisation of fibres. Fibres arrengement before expansion of matrix. Pores are open.

FIGURE 29: Fibres rearrengement after expansion of matrix.. Pores are closed. (Expansion produced by balloon underneath membrane being inflated)

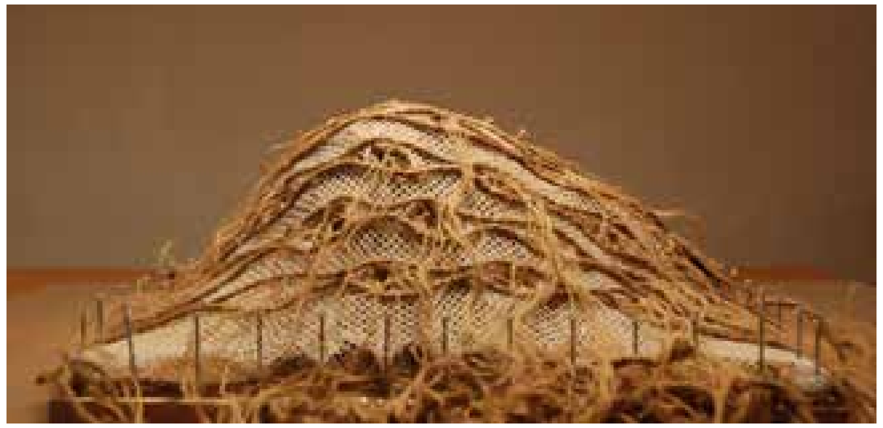


FIGURE 30: Model based on anisotropical stiffness of cuticle. Different layers have been added being treated with different polymers: latex, wood glue, epoxy resin.trying to achieve a multilayered material with different degrees of flexibility. Filaments through the pores are connecting the layers.

FIGURE 31: View from the interior. Fiber rearrengement around open pores.

Chapter 06
Application to
Architecture

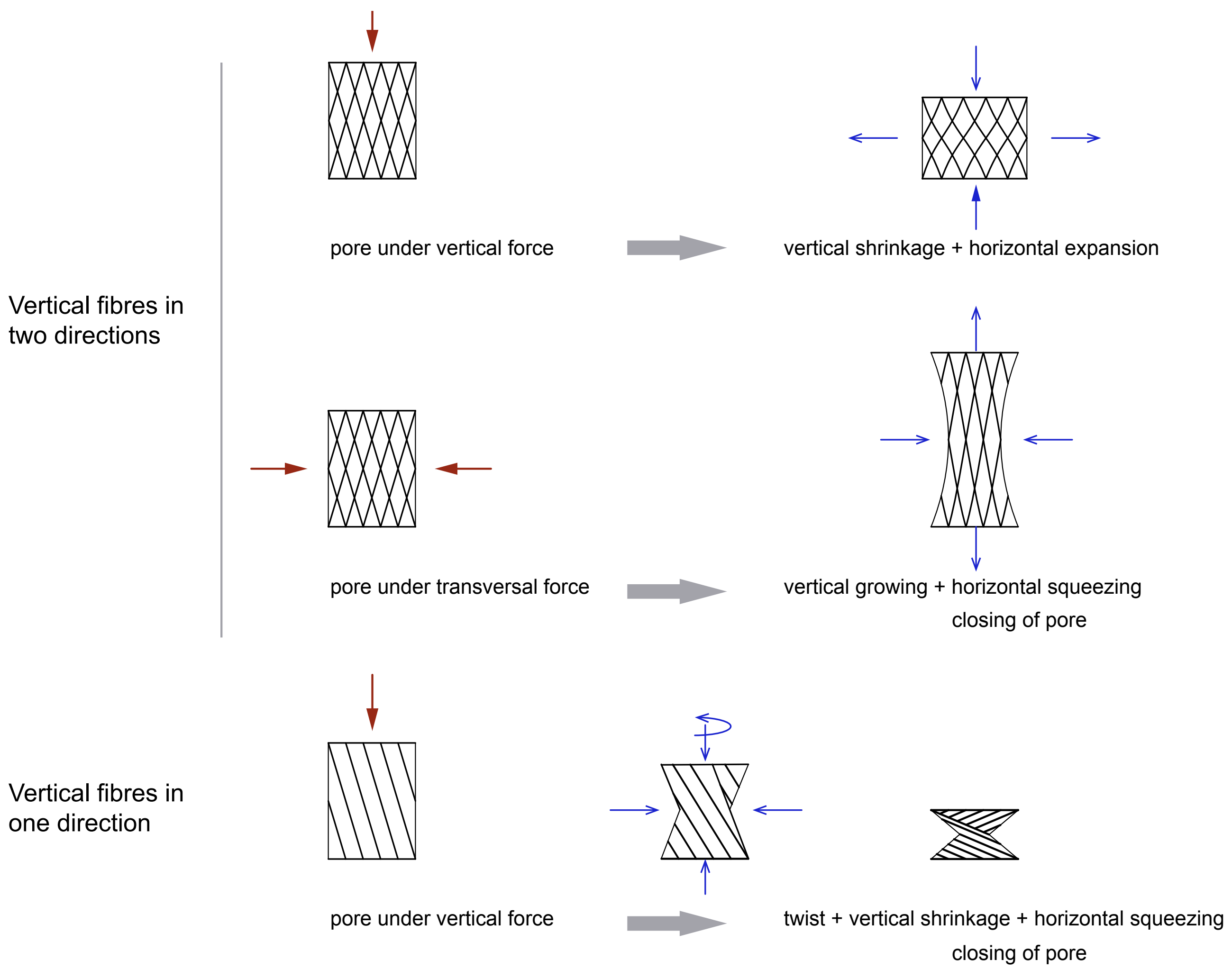


FIGURE 32: Range of possible transformations of openings.

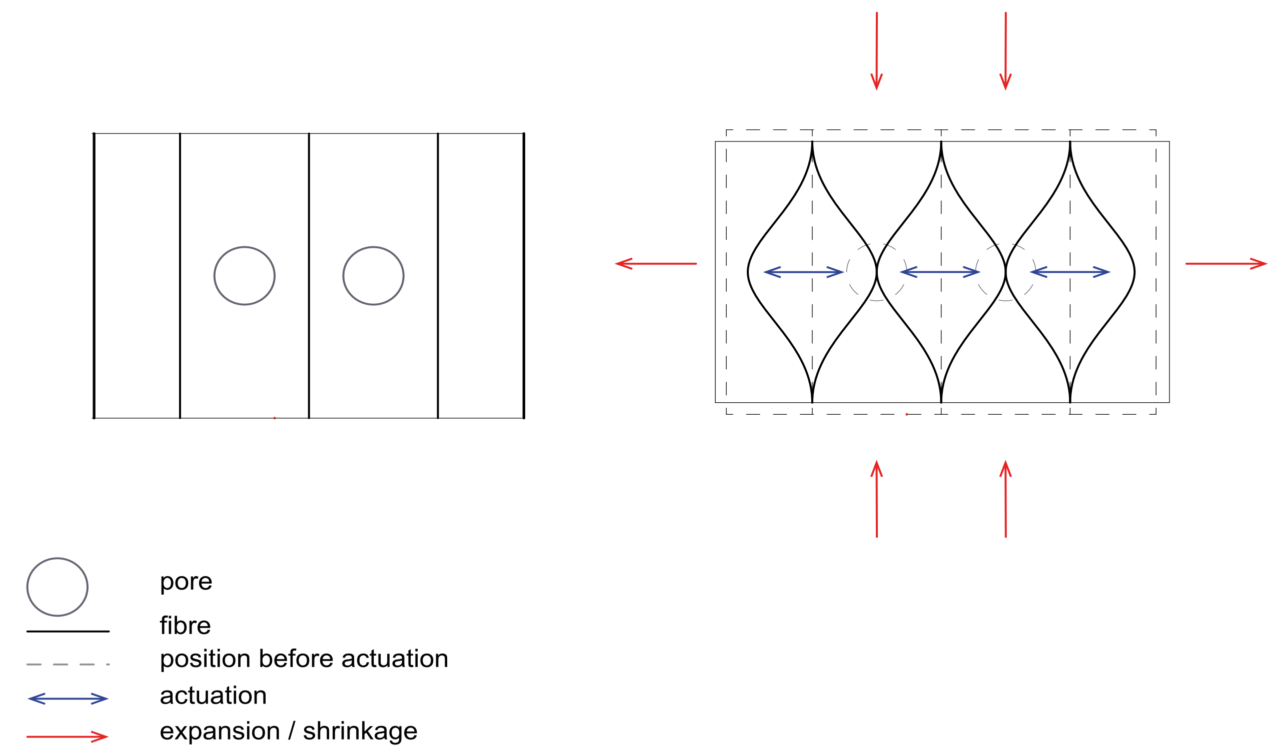


FIGURE 33: Local actuation causes change of global geometry

APPLICATION TO ARCHITECTURE

Architectural shell has two general layers
1.Outer schlerites bear structural loads.
2.Inner "endocuticle" plays two roles: structural- holding schlerites together and performative- opening and closing pores in response to environmental conditions.
As in biological role model, architectural "endocuticle" has fibrous layers and vertical filament running through pores.
Under the schlerites pores play role of reinforcement, between the schlerites the pores can conduct air or water.
In architectural model "endocuticle" is a 3D-weaved fiber system, which is able to stretch and store elastic energy.

Range of possible transformations of openings and connecting fibers.
Fibers of horisontal layers connect and define shape of openings. Range of transformations of openings and connections between them (layers of fibers connecting and shaping the openings may cause compression or rotation of openings according to the disposition and actuation of fibers in layers and disposition of fibers on vertical sides of openings) allows a range of various transformations.

Actuation
There are two possible types of actuation for this system:
1. Linear actuator - bimetall or memory shape alloy.
2. Volumetric actuator - hydrogel or pneumatic element laminated in composite material.

Local actuation causes change of global geometry.
When fibers are actuated, the pores are closed, if actuator continues to deform or expand, the deformation of global geometry begins. Thus, following internal rules, global geometry can be rearranged according to changing weather conditions.

The most important weather elements of interest for responsive architectural skin, together with their corresponding implications are:
1. dry bulb air temperature - thermal comfort, heating and cooling;
3. precipitation - drainage, loading, damage;
4. wind speed and direction - energy, ventilation, comfort, loading;
5. solar radiation - daylight availability and useful solar heat gains;

Responsive architectural skin
According to the combination of external and internal variables, architectural shape can respond differently in different zones of the shell, rearrange itself and control heat flow, air flow, rain penetration, and light.

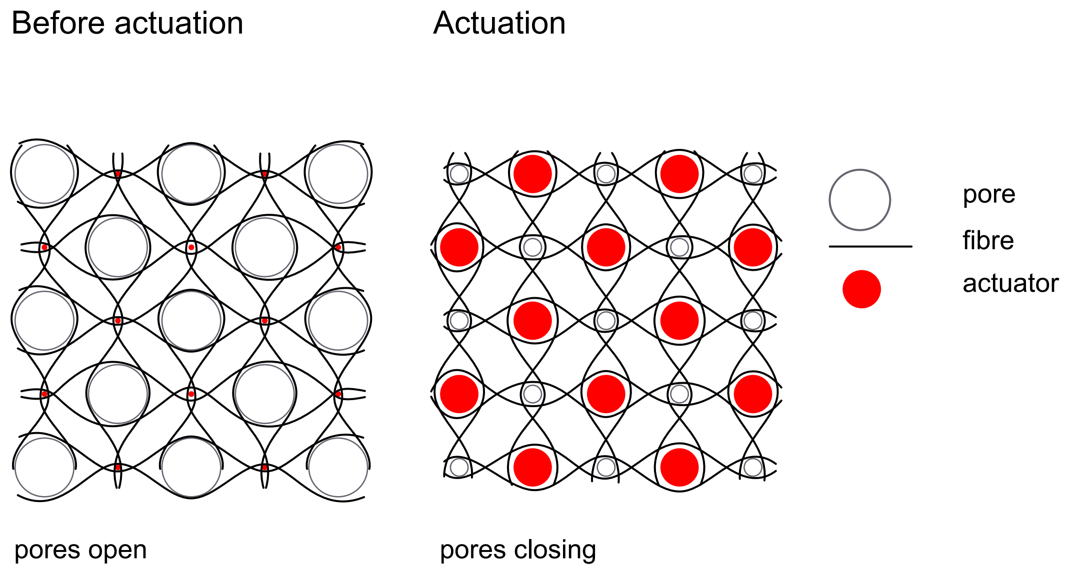


FIGURE 34: Fibers in layers and pore canals direct the way pores close (compression). Fibers are not expanding, they are changing their position.

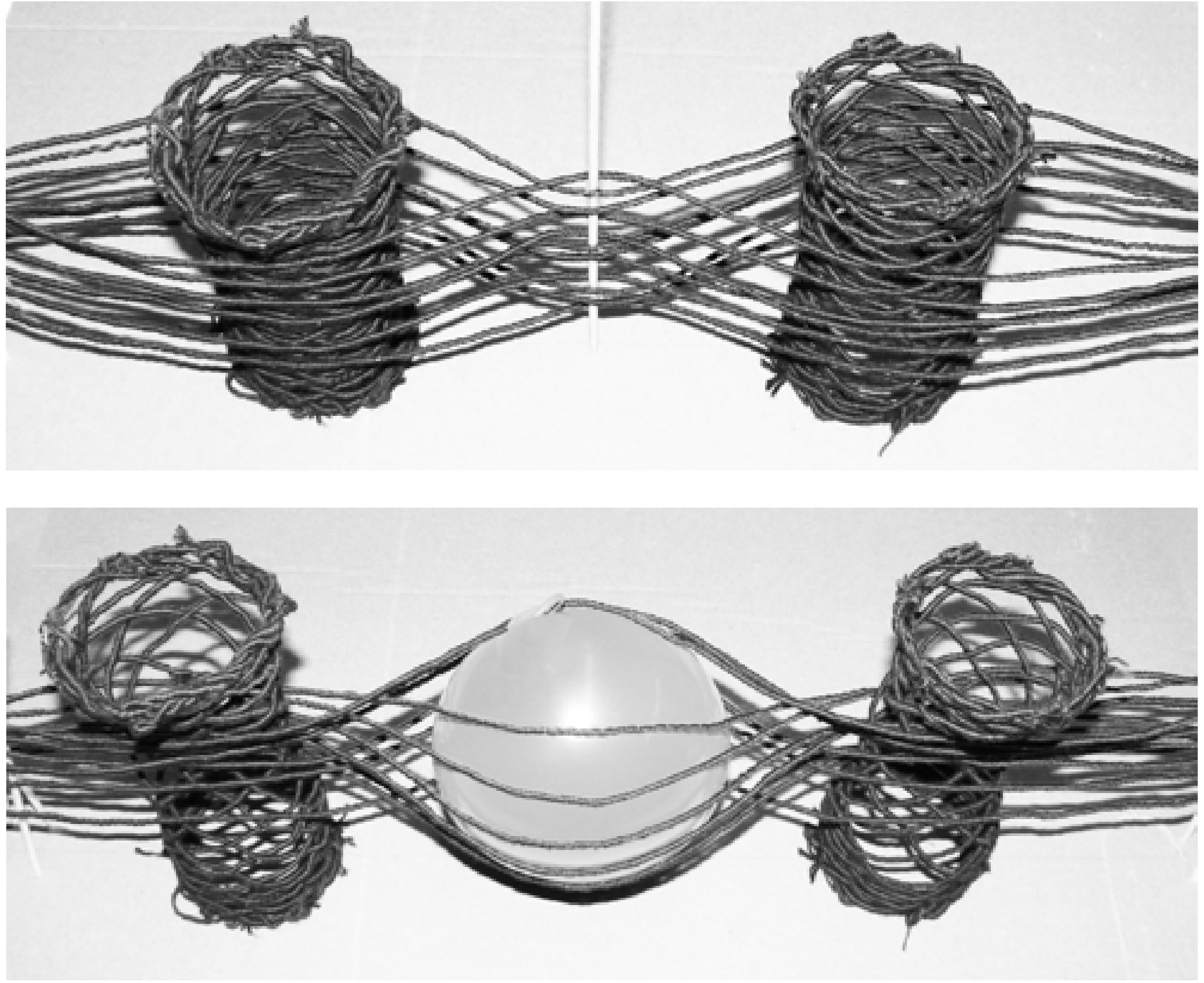


FIGURE 35: Fibers in layers and pore canals direct the way pores close (compression). Experiment.

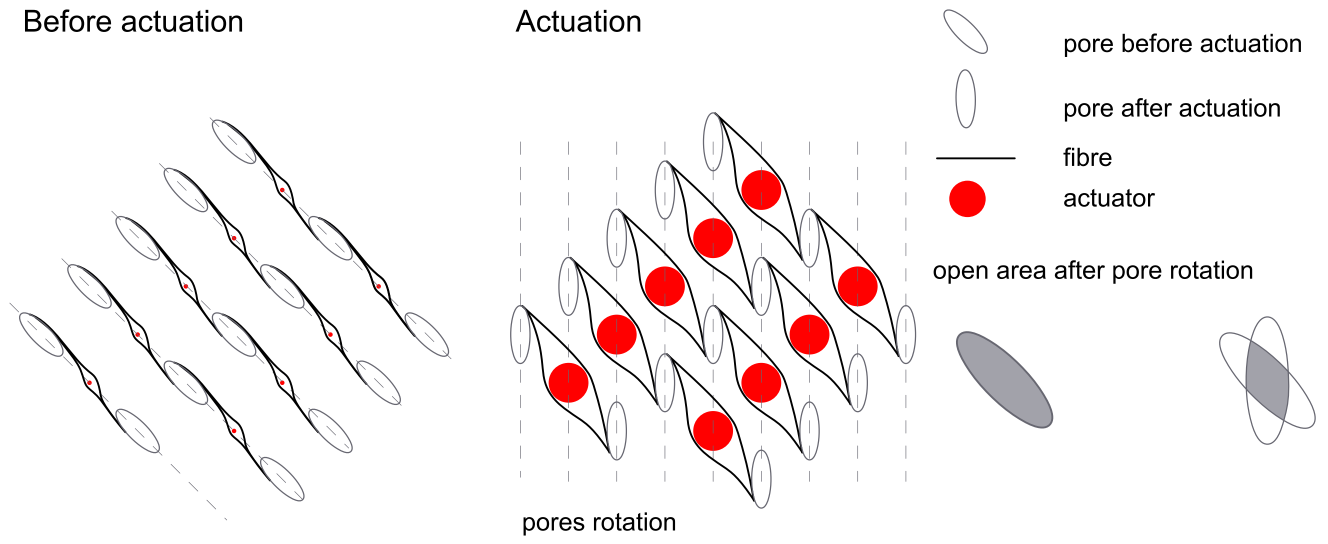


FIGURE 36: Fibers in layers and pore canals direct the way pores close (rotation).

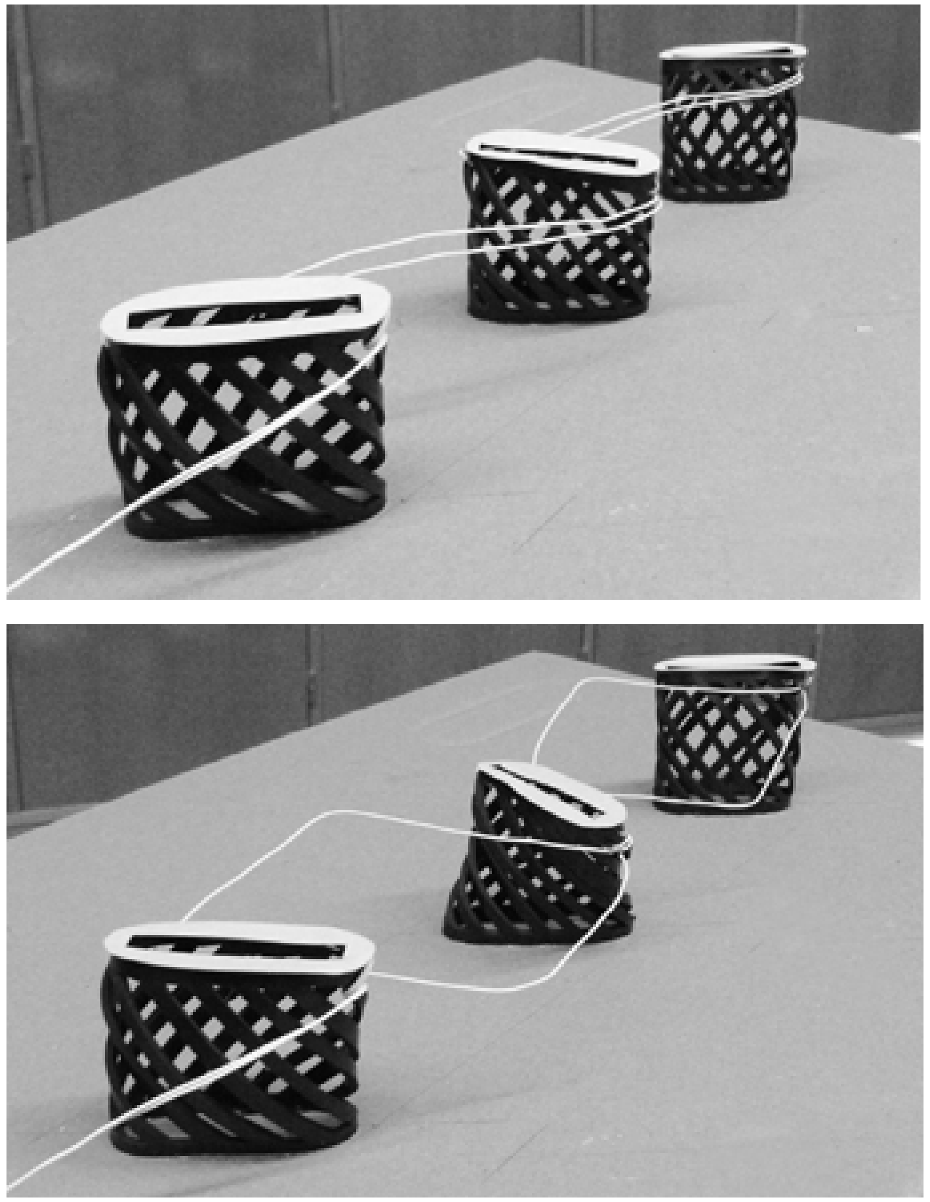


FIGURE 37: Fibers in layers and pore canals direct the way pores close (rotation). Experiment.

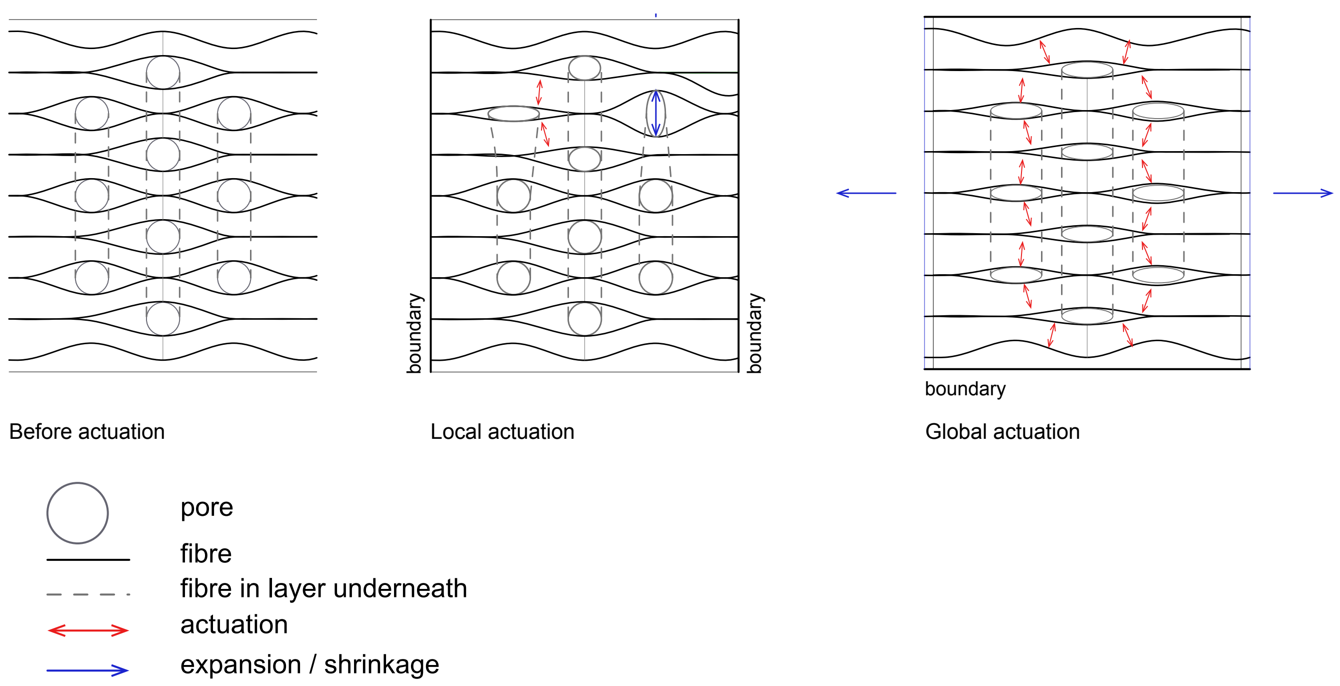


FIGURE 38: Fiber reorganisation following actuation

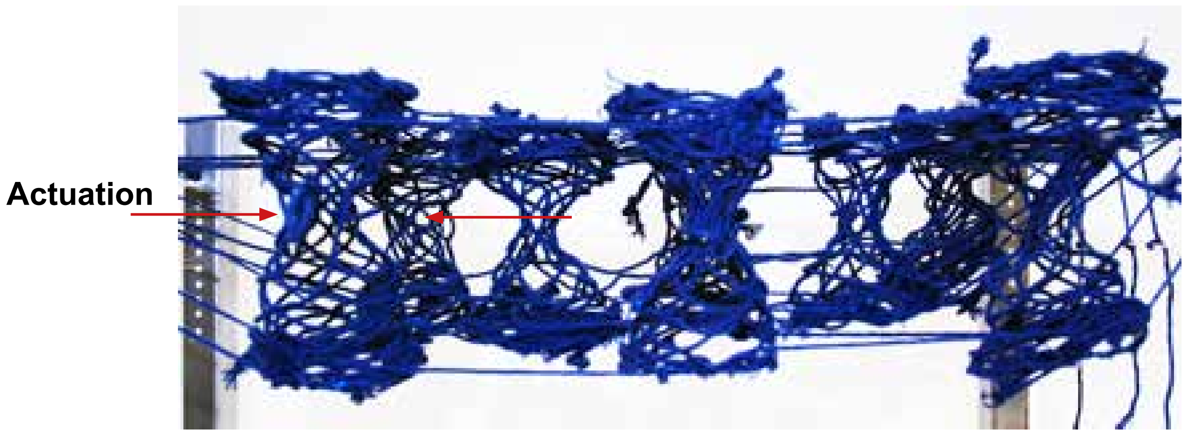


FIGURE 39: Model of pore canals system made with wire wrapped by wool. Front view. Growth in height of squeezed pores.

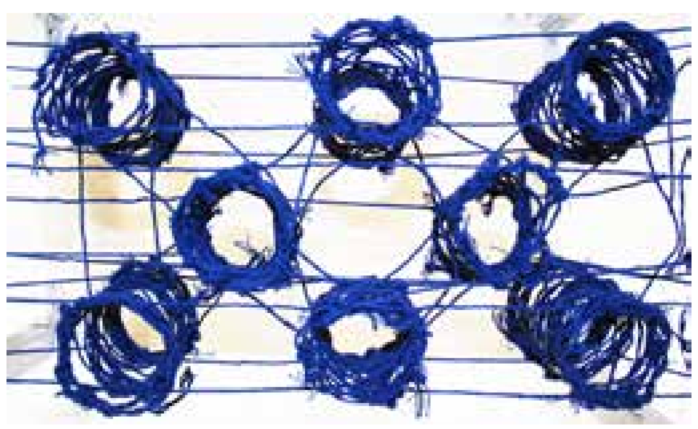


FIGURE 40: Model made with wire wrapped by wool. Top view. Upper layer of fibers tensed to achieve more rigidity. Bottom layer more flexible.

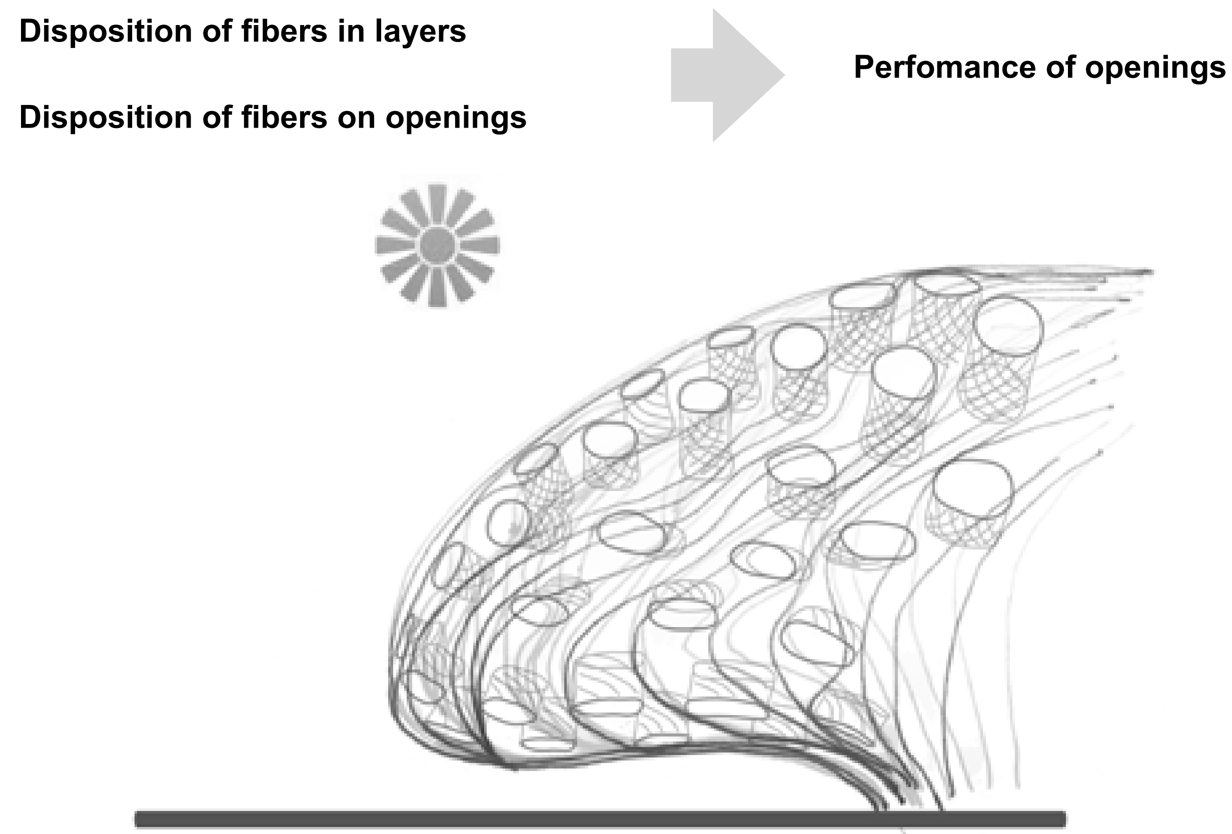


FIGURE 41: Fibers connect and define shape of openings.

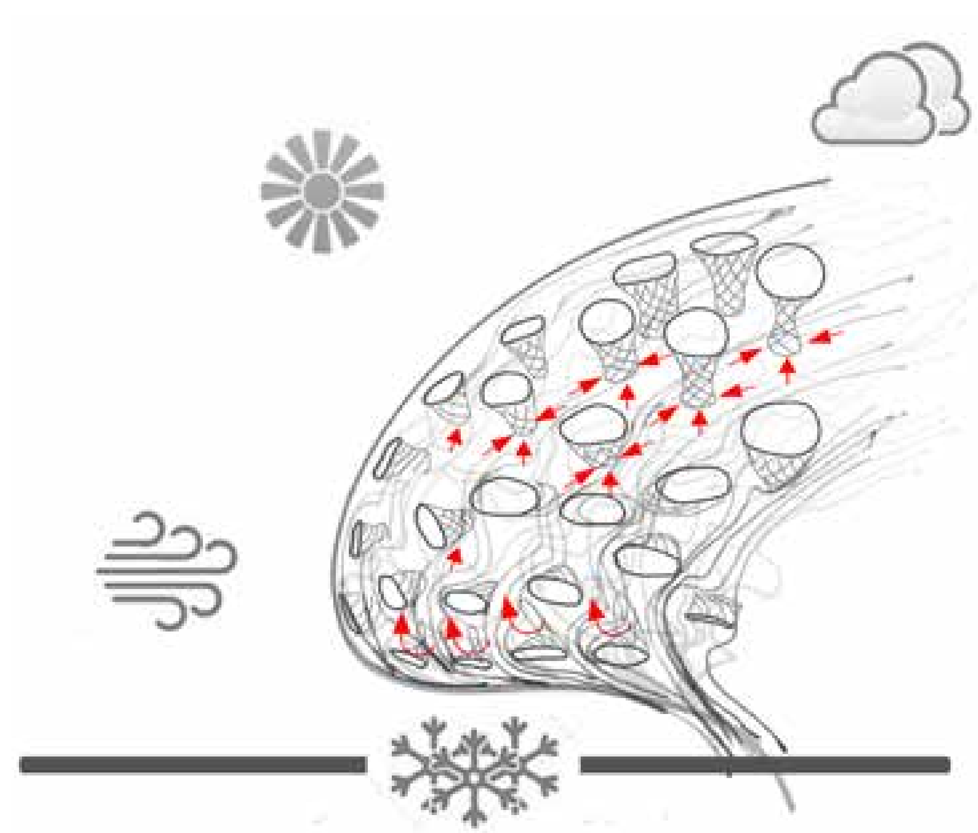


FIGURE 42: According to the combination of external and internal variables, architectural shape can respond differently in different zones of the shell and rearrange itself.

Chapter 07
Fabrication

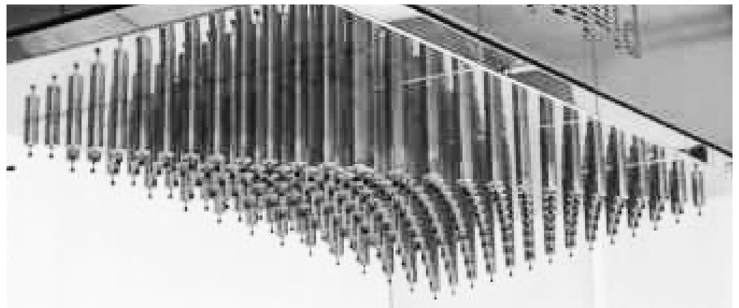


FIGURE 43: Wooden, bamboo or plastic sticks hanging, serving as a guide for the robot.

FIGURE 44: Hanging pores from auxiliar scaffolding.

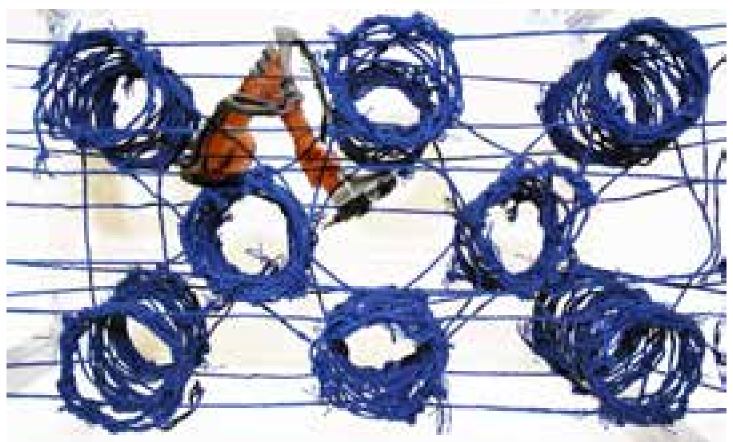


FIGURE 45: Filament winding by Kuka from underneath to conect and shape the pores.

FABRICATION

The arthropod is building its cuticle from the inside, producing the layers starting from the most exterior. When secreted, before the ecdysis, this layers are still hydrated and flexible. The animal then expands or shrinks to get the right shape. It'sonly after that when the epicuticle and exocuticle become tanned, sclerotized, loosing water and becoming stiffer.
We try to abstract this process to develop the fabrication method.

The fabrication of the system of pores interconnected by the horizontal layoutof of fibers with different orientations could be achieved by using kuka robots.

We propose two options:

Option A
Vertical woodden, bamboo or plastic sticks hanging from an auxiliary structure would serve as the guide for the simultaneous winding of pores and horizontal oriented fibers. The robot, working from underneath, will start building the most exterior and more stiff layer, using prepreg fibers with non flexible polymer. This first layers will be strongly pretensed before curing.
Gradually, to the bottom layers, the fibers will be pre-peg with more flexible polymers (e.g. polyurethane based, latex...). The movement and velocity of the robot will affect the final shape of the system.

Option B
In that option we propose the pre-braiding of the pores to simplify and speed the process. The pre-braided pores would be then hanged from the auxiliary structure, being the rest of the fabrication process as explained in option A.

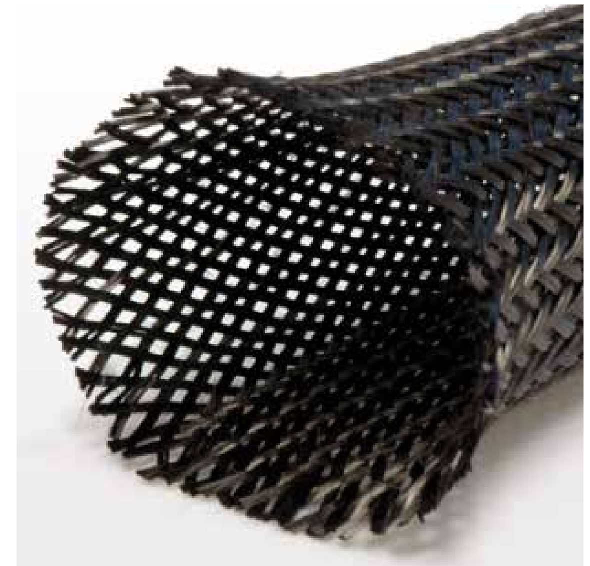


FIGURE 46: Option A. Pre-braiding of pore structures and subsequent layout of fibers in horizontal layers by Kuka (Source: http://www.easycomposites.co.uk/)

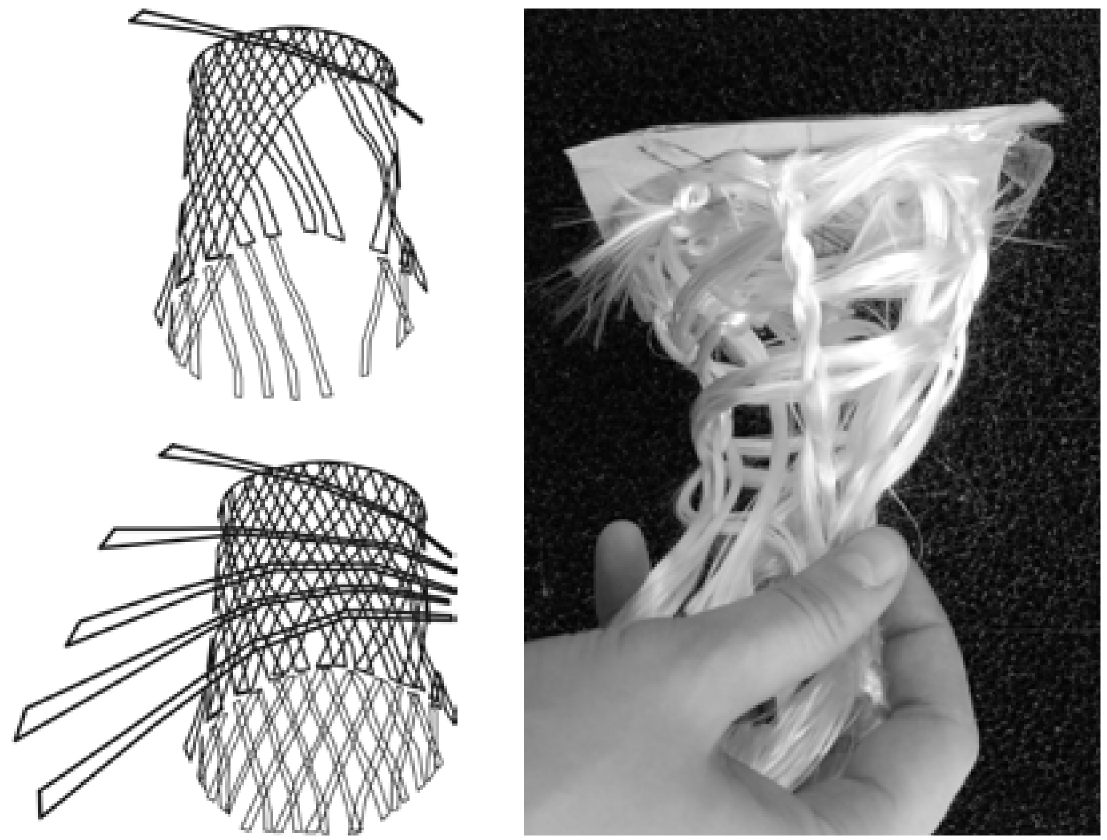


FIGURE 47: Option B. 3D-braiding of pore structures simultaneously with layout of horizontal layers of fibers by Kuka.

Chapter 08
Appendix

Bibliography

Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975.

Attachement Devices of Insect cuticle. Stanislav Gorb. Kluwer Academic Publishers. 2001.

Arthropod Biology and Evolution. Edited by A.Minelli, G.Boxshall, G.Fusco. Springer. 2013.

Design and mechanical properties of insect cuticle. Julian F.V. Vincent, Ulrike G.K.Wegst. 2004.

The physiolog y of insecta. Volume 6. Moris Pockstein.

Chitin in the exoskeleton of Arthropoda: from an ancient design to novel materials science. H.Fabritius.

Pore canal shape related to molecular architecture of arthropod cuticle. A.C.Neville, M.G.Thomas, B.Zelazny.

Pore canals and related structures in insect cuticle. M. Locke. The Journal of Biophysical and Biochemical Cytology. Volume 10, 1961.

A study of the physical and chemical properties of the insect cuticle. G.Fraenkel, K.M.Rudall.

Insect biochemistry and molecular biology. B.Moussian.Elsevier.

Recent advances in understanding mechanisms of insect cuticle differentiation. B.Moussian.Elsevier.

The exoskeleton of the lobster Homarus Americanus as an example of a smart anisotropic biological material. P. Romano, H. Fabritius, D. Raabe. Max Plank Institute for Iron Research (October 2006)

Image Analyses of Two Crustaceans Exoskeletons and Implications of the Exoskeletal Microstructure on the Mechanical Behavior. Liang Cheng. Lyun Wang. Anette M. Karlsson.

Permeability of Insect Cuticle to Water and lipids. M. Locke. Department of Biology, Western Reserve University, Cleveland, Ohio.

Pore Structures in Insect Olfatory Sensilla: A Review of Data and Concepts. Rudolf Alexander Steinbrecht. Max-Planck-Institut für Verhaltenphysiologie Seewiesen, Arbeitsgruppe Kaissling, Postfach 1564, D-82305 Starnberg, Germany. (April 1997).

Biomimetics: Lessons from nature, an overview. Bharat Bhushau. The Royal Society.

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Chapter 01: Introduction

01: Biology of the Arthropod Cuticle. A.C. Neville. Springer-Verlag. 1975, p.191, Fig.5.35.

Chapter 02: Cuticle Composition

03: The exoskeleton of the lobster Homarus americanus as an example of a smart anisotropic biological material. P. Romano, H. Fabritius, D. Raabe.Max Plank Institute for Iron Research (October 2006).

04: Pore canals and related structures in insect cuticle. M. Locke. The Journal of Biophysical and Biochemical Cytology. Volume 10, 1961.

Chapter 03: Types of Cuticle

05: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975. P.7, Fig.2.1 (A).

06: J Exp Biol. October 2001. vol. 204 no. 20 3531-3545 (Adapted from Rose et al., 2000).

Chapter 04: Studied Cuticle Principles

07: Attachement Devices of Insect cuticle. Stanislav Gorb. Kluwer Academic Publishers. 2001.

08: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975. P.8, Fig.2.1 (B).

09: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975. P.295, Fig.6.29.

10: Biology of the arthropod Cuticle. A.C.Neville. Springer-Verlag. 1975. P.181, Fig.5.25.

11: The exoskeleton of the lobster Homarus americanus as an example of a smart anisotropic biological material. P. Romano, H. Fabritius, D. Raabe.

12: Attachement Devices of Insect cuticle. Stanislav Gorb. Kluwer Academic Publishers. 2001.

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43: Source: http://fdtechnologies.eu/

46: Source: http://www.easycomposites.co.uk/